SAFEGUARDING THE OZONE LAYER AND THE GLOBAL CLIMATE SYSTEM

SAFEGUARDING THE OZONE LAYER AND THE GLOBAL CLIMATE SYSTEM

Issues Related to Hydrofluorocarbons and Perfluorocarbons

Summary for Policymakers and Technical Summary

WMO

Intergovernmental Panel on Climate Change
Technology and Economic Assessment Panel

UNEP

IPCC/TEAP Special Report on

Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons

Summary for Policymakers

A Report of Working Groups I and III of the IPCC

and

Technical Summary

A Report accepted by Working Groups I and III of the IPCC but not approved in detail

This report was produced by the Intergovernmental Panel on Climate Change (IPCC) and the
Technology and Economic Assessment Panel (TEAP) on the invitation of the United Nations
Framework Convention on Climate Change and the Montreal Protocol
ISBN 92-9169-118-6

Foreword

The Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988 to assess available information on the science, the impacts, and the economics of, and the options for mitigating and/or adapting to, climate change. In addition, the IPCC provides, on request, scientific, technical, and socio-economic advice to the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC). The IPCC has produced a series of Assessment Reports, Special Reports, Technical Papers, methodologies, and other products that have become standard works of reference and that are widely used by policymakers, scientists, and other experts.

The *Special Report on Safeguarding the Ozone Layer and the Global Climate System* was developed in response to invitations by the United Nations Framework Convention on Climate Change (UNFCCC)[1] and the Montreal Protocol on Substances that Deplete the Ozone Layer[2]. IPCC and the Montreal Protocol's Technology and Economic Assessment Panel (TEAP) were asked to work together to develop a balanced scientific, technical and policy-relevant Special Report. The request covered both a scientific assessment of the interrelations between the ozone layer and climate change and development of user-friendly and policy-neutral information to assist all Parties and stakeholders in making informed decisions when evaluating alternatives to ozone-depleting substances.

Discussions on these topics have a long history, including deliberations at the Fourth Conference of the Parties to the UNFCCC (held in 1998 in Buenos Aires) which invited Parties and all other relevant entities to provide information to the UNFCCC Secretariat on available and potential ways and means of limiting emissions of hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) when used as replacements for ozone depleting substances. In 1999, an IPCC/TEAP Expert Meeting was organized[3], which addressed the issue and forms important background for the present effort, along with new information on science, technology, and policy needs.

After the decision of the Eighth Conference of the Parties to the UNFCCC[1], the Fourteenth Meeting of the Parties to the Montreal Protocol (Rome, Italy, 25-29 November 2002), welcomed this decision, and requested the TEAP to work with the IPCC in preparing the Special Report, and requested simultaneous submission of the report to the Open Ended Working Group under The Montreal Protocol and the UNFCCC SBSTA. The scope, structure, and outline of the Special Report were approved by the IPCC in plenary meetings during its Twentieth Session in Paris, France, from 19-21 February 2003.

As is usual in the IPCC, success in producing this report has depended first and foremost on the enthusiasm and cooperation of experts worldwide in many related but different disciplines. We would like to express our gratitude to all the Coordinating Lead Authors, Lead Authors, Contributing Authors, Review Editors, and Expert Reviewers. These individuals have devoted enormous time and effort to produce this report and we are extremely grateful for their commitment to the IPCC process.

We would also like to express our sincere thanks to the Steering Committee for this Report, which consisted of co-chairs from both the Technology and Economic Assessment Panel (TEAP) and the Intergovernmental Panel on Climate Change (IPCC):

> Stephen Andersen, Lambert Kuijpers, and José Pons
> for the Technology and Economic Assessment Panel (TEAP),
> and
>
> Susan Solomon, Ogunlade Davidson and Bert Metz (chair of the Steering Committee)
> for the Intergovernmental Panel on Climate Change (IPCC).

We are convinced that this Special Report provides a balanced scientific, technical and policy-related assessment that will assist all concerned in taking decisions when considering alternatives to ozone-depleting substances.

Michel Jarraud
Secretary-General,
World Meteorological Organization

Klaus Töpfer
Executive Director,
United Nations Environment Programme and
Director-General,
United Nations Office in Nairobi

---

[1] Decision 12/CP.8, FCCC/CP/2002/7/Add.1, page 30. Eight Conference of the Parties to the UNFCCC, New Delhi, India, 23 October – 1 November 2002

[2] Decision XIV/10 UNEP/OzL.Pro.14/9, page 42. Fourteenth Meeting of the Parties to the Montreal Protocol, Rome, Italy, 25-29 November 2002

[3] Proceedings of the Joint IPCC/TEAP Expert Meeting on options for the limitation of emissions of HFCs and PFCs, Petten, The Netherlands, 26-28 May 1999, see http://www.ipcc-wg3.org/docs/IPCC-TEAP99/index.html

Preface

This *Special Report on Safeguarding the Ozone and the Global Climate System* has been developed in response to invitations from Parties to the UNFCCC and the Montreal Protocol. It provides information relevant to decision-making in regard to safeguarding the ozone layer and the global climate system: two global environmental issues involving complex scientific and technical considerations. The scope, structure, and outline of this Special Report were approved by the IPCC at its Twentieth Session in Paris, France, 19–21 February 2003. The responsibility for preparing the report was given jointly to IPCC's Working Groups I and III and the Montreal Protocol's Technology and Economic Assessment Panel (TEAP). A joint IPCC/ TEAP Steering Committee (see below) was established to manage preparation of the report following IPCC procedures.

Background

Scientific evidence linking chlorofluorocarbons (CFCs) and other Ozone Depleting Substances (ODSs) to global ozone depletion led to the initial control of chemicals under the 1987 Montreal Protocol and to Amendments and Adjustments in the 1990s that added additional ODSs, agreed phaseouts, and accelerated those phaseouts. This international process has resulted in (i) elimination of production of most CFCs, methyl chloroform, and halons, (ii) the increased use of existing hydrochlorofluorocarbons (HCFCs), (iii) the new production of a wide range of industrial fluorine containing chemicals, including new types of HCFCs, hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), (iv) use of non-halogenated chemical substitutes such as hydrocarbons, carbon dioxide and ammonia and (v) the development of not-in-kind alternative methods such as water-based cleaning procedures.

The likelihood that CFCs and other ODSs also affect the climate system was first identified in the 1970s, and the global warming effectiveness of halocarbons, including HFCs, has been further elucidated over the past three decades. For example, the 1989 Scientific Assessment of Stratospheric Ozone included a chapter on halocarbon global warming potentials (GWPs) and the 1989 Technology Assessment presented these GWPs in discussions of the importance of energy efficiency in insulating foam, refrigeration, and air conditioning. As various approaches were developed to the phase-out of ODSs under the Montreal Protocol, it was realized that some actions taken to reduce future depletion of the ozone layer, in particular the introduction of HFCs and PFCs, could increase or decrease global warming impact.

This scientific and technical information allowed Parties to the Montreal Protocol to choose options to replace ODSs, mindful of the global warming impact and was reflected in some investment decisions under the Montreal Protocol Multilateral Fund. When the Kyoto Protocol was negotiated in 1997, countries had new incentives to take account of how choices among substitutes could affect the objectives of both protocols. These considerations created a need for more comprehensive information regarding options for ODS replacement that take into account the need of safeguarding the ozone layer as well as the global climate system. In May 1999, the IPCC and TEAP held a joint expert meeting on options for the limitation of Emissions of HFCs and PFCs and in October 1999 TEAP published its report: "The implications to the Montreal Protocol of the Inclusion of HFCs and PFCs in the Kyoto Protocol". This Special Report of 2005 is the latest cooperative effort.

The potential of each ODS substitute to influence the climate system depends not only upon the physical and chemical properties of the substance itself but also upon the factors that influence emissions to the atmosphere, such as containment, recycling, destruction and energy efficiency in particular applications. Gases, applications and sectors considered in the report are those related to emissions of CFCs, HCFCs, HFCs and PFCs, as well as to alternatives for the use of HFCs and PFCs. The report does not consider unrelated industrial or other uses of the same chemicals The report covers chemicals and technologies in use or likely to be used in the next decade.

Organization of the Report

The report provides the scientific context required for consideration of choices among alternatives to ODSs (chapters 1 and 2); potential methodologies for assessing options (chapter 3); and technical issues relating to GHG emission reduction opportunities for each of the sectors involved, including refrigeration, air conditioning, foams, aerosols, fire protection and solvents (chapters 4 to 10). The report also addresses the future availability of HFCs (chapter 11).

Chapters 1 and 2 address linkages between ozone depletion and climate change, and draw from previous international scientific assessments, particularly the periodic assessments conducted under the auspices of WMO, UNEP, and the IPCC (e.g., the most recent *Scientific Assessment of Ozone Depletion, 2002*, the *Assessment of the Environmental Impacts of Ozone Depletion, 2002*, and *Climate Change: The Scientific Basis, 2001*). Chapter 1 covers stratospheric chemistry and dynamics and their coupling to climate change, while chapter 2 covers radiative forcing of each of the relevant gases as well as their roles in tropospheric chemistry and air quality. The present report does not seek to cover the breadth and depth of the more specialized ozone and climate change assessments, but rather to provide a summary of relevant interactions between the two environmental issues to aid the understanding and application of the rest of the report.

Chapter 3 summarizes available methodologies to characterize or compare technologies (such as the lifecycle climate performance parameter, LCCP), particularly those approaches that are applied across the diverse sectors covered in this report.

Chapters 4 through 10 then provide technical descriptions and information for each of the key sectors of halocarbon use: refrigeration (4), residential and commercial air conditioning and heating (5), mobile air conditioning (6), foams (7), medical aerosols (8), fire protection (9), and non-medical aerosols, solvents and HFC-23 byproduct emissions from HCFC-22 production (10). Each chapter provides an overview of its sector, the relevant technologies, information on consumption and emission of relevant gases, and practices and alternative technologies to reduce emissions and net warming impacts. This includes consideration of process improvement in applications, improved containment, recovery and recycling during operation, end-of-life recovery, disposal and destruction. The choices among options within each sector involve detailed consideration of technical factors including performance, environmental health and safety, cost, availability of alternatives, and total energy and resource efficiencies.

Chapter 11 covers both supply and demand issues for HFCs, and integrates emissions estimates across sectors and regions. It aggregates the emissions information for various chemicals from the various sectors, and considers the balance between supply and demand of HFCs.

As in past IPCC reports, this report contains a Summary for Policymakers (SPM) and a Technical Summary (TS), in addition to the main chapters. Each section of the SPM and TS has been referenced to the appropriate section of the relevant chapter, so that material in the SPM and TS can easily be followed up in further detail in the chapters. The report also contains annexes with a the list of Authors and Expert Reviewers, a glossary, a list of acronyms and abbreviations, a list of units and conversion factors, and an overview of major chemical formulae and nomenclature of substances that are considered in this report.

The report was compiled between August 2003 and April 2005 by 145 experts from 35 countries. The draft report was circulated for review by experts, which submitted valuable suggestions for improvement. This was followed by a second review by both governments and experts. In these two review rounds, about 6600 comments were received from about 175 experts, governments and non-governmental organizations. This review process, and its oversight by Review Editors who are independent of the author teams, is an intrinsic part of any IPCC assessment and is an important part of ensuring the quality and credibility of the product.

The final report was considered by a joint Session of IPCC Working Groups I and III held in Addis Ababa from April 6th to 8th, 2005, where the SPM was approved line-by-line and the underlying report was accepted by the IPCC Panel.

Acknowledgements

The Steering Committee sincerely appreciates all the Coordinating Lead Authors, Lead Authors, and Review Editors whose expertise, diligence, and patience have underpinned the successful completion of this report and who generously contributed substantial amounts of their professional and personal time, and the contribution of the many contributors and reviewers for their valuable and painstaking dedication and work.

We also thank Marco Gonzalez and Megumi Seki from UNEP's Ozone Secretariat, for their co-sponshorship, financial support and commitment to the process that led to this report.

We thank the Governments of the Netherlands, United States of America, Japan, and Argentina for hosting the four report drafting meetings, and the Government of Ethiopia and the United Nations Centre in Addis Ababa for hosting the Joint Working Group I and III Session.

We also thank Renate Christ, Secretary of the IPCC, and the staff of the IPCC Secretariat, who provided logistical support for government liaison and travel of experts from the developing and transitional economy countries.

Finally we also thank the staff of the Working Groups I and III Technical Support Units, for their work in preparing the report, in particular David de Jager (Secretary of the Steering Committee, TSU WG III), Martin Manning (Head TSU WG I), Leo Meyer (Head TSU WG III) for their scientific and management support, and Tahl Kestin, Scott Longmore, Melinda Tignor (WGI), Heleen de Coninck, Anita Meier, Martin Middelburg, Rob Puijk, and Thelma van den Brink (WG III) for their technical and logistic support. Special thanks to Christine Ennis, Dave Thomas and Pete Thomas for their contribution to the copy-editing of the final draft of this report.

The Steering Committee for this Report:
Stephen O. Andersen, Co-Chair of the TEAP
Ogunlade Davidson, Co-Chair of IPCC Working Group III
Lambert Kuijpers, Co-Chair of the TEAP
Bert Metz, Co-Chair of IPCC Working Group III (Chair of the Steering Committee)
José Pons, Co-Chair of the TEAP
Susan Solomon, Co-Chair of IPCC Working Group I

Contents

Summary for Policymakers

1. Introduction 2

2. Halocarbons, ozone depletion and climate change 4
- 2.1 What are the past and present effects of ODSs and their substitutes on the Earth's climate and the ozone layer? 4
- 2.2 How does the phase-out of ODSs affect efforts to address climate change and ozone depletion? 5
- 2.3 What are the implications of substitu-tion of ODSs for air quality and other environmental issues relating to atmospheric chemistry? 6

3. Production, banks and emissions 8
- 3.1 How are production, banks and emissions related in any particular year? 8
- 3.2 What can observations of atmospheric concentrations tell us about banks and emissions? 8
- 3.3 How are estimated banks and emissions projected to develop in the period 2002 to 2015? 8

4. Options for ODS phase-out and reducing greenhouse gas emissions 11
- 4.1 What major opportunities have been identified for reductions of greenhouse gas emissions and how can they be assessed? 11
- 4.2 What are the sectoral emission reduction potentials in 2015 and what are associated costs? 12
- 4.3 What are the current policies, measures and instruments? 14
- 4.4 What can be said about availability of HFCs/PFCs in the future for use in developing countries? 14

Technical Summary

1. Introduction 16

2. Halocarbons, ozone depletion and climate change 18
- 2.1 How do the CFCs and their replacements contribute to the radiative forcing of the climate system? 18
- 2.2 How long do CFCs and their replacements remain in the atmosphere after they are emitted? 19
- 2.3 How are the atmospheric concentrations and emissions of CFCs, halons, HCFCs, HFCs and PFCs changing? 20
- 2.4 How much do the halocarbon gases and their replacements contribute to positive radiative forcing of the climate system relative to pre-industrial times? What about relative to 1970? 22
- 2.5 How has stratospheric ozone changed in recent decades and why? 23
- 2.6 How has ozone depletion affected the radiative forcing of the climate system? 23
- 2.7 What factors are expected to control ozone in the coming century? Will it 'recover' to pre-ozone-hole values? Has the recovery already begun? 24
- 2.8 How much are CFCs, HCFCs and their possible replacements expected to affect the future radiative forcing of the climate system? 25
- 2.9 What is the global warming potential and how is it used? 26
- 2.10 Are HCFCs, HFCs or their replacements expected to have other effects on future environmental chemistry? 28

3. Options for ODS phase-out and reducing GHG emissions 29

- 3.1 Where do GHG emissions occur that are related to the use of ODSs and their substitutes? 29
- 3.2 How are estimated banks and emissions projected to develop during the period 2002 to 2015? 29
- 3.3 Which options are available for reducing GHG emissions? 36
- 3.4 Which assessment tools can provide information on technology choices? 36
- 3.5 What are regional differences? 39
- 3.6 What major opportunities have been identified for reducing GHG emissions associated with the use of ODSs, their substitutes and related indirect emissions? 39

3.7 Which policy instruments are available to achieve the reductions in the emissions of GHGs addressed in this report? 46
3.8 What can be said about the future availability of HFCs/PFCs for use in developing countries? 46

4. Important findings for sectors using ODSs and their alternatives 48
4.1 What are the most important findings for the refrigeration sector? 48
4.2 What are the most important findings for residential and commercial air conditioning and heating? 55
4.3 What are the most important findings for mobile air conditioning? 57
4.4 What are the most important findings for foams? 60
4.5 What are the most important findings for medical aerosols? 67
4.6 What are the most important findings for fire protection? 69
4.7 What are the most important findings for non-medical aerosols and solvents and for HFC-23 emissions? 74

Annex I Glossary of terms 81

Annex II Major Chemical Formulae and Nomenclure 85

IPCC/TEAP Special Report

Safeguarding the Ozone Layer and the Global Climate System:
Issues Related to Hydrofluorocarbons and Perfluorocarbons

Summary for Policymakers

1. Introduction

This IPCC Special Report was developed in response to invitations by the *United Nations Framework Convention on Climate Change* (UNFCCC)[1] and the *Montreal Protocol on Substances that Deplete the Ozone Layer*[2] to prepare a balanced scientific, technical and policy relevant report regarding alternatives to ozone-depleting substances (ODSs) that affect the global climate system. It has been prepared by the IPCC and the Technology and Economic Assessment Panel (TEAP) of the Montreal Protocol.

Because ODSs cause depletion of the stratospheric ozone layer[3], their production and consumption are controlled under the Montreal Protocol and consequently are being phased out, with efforts made by both developed and developing country parties to the Montreal Protocol. Both the ODSs and a number of their substitutes are greenhouse gases (GHGs) which contribute to climate change (see Figure SPM-1). Some ODS substitutes, in particular hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs),

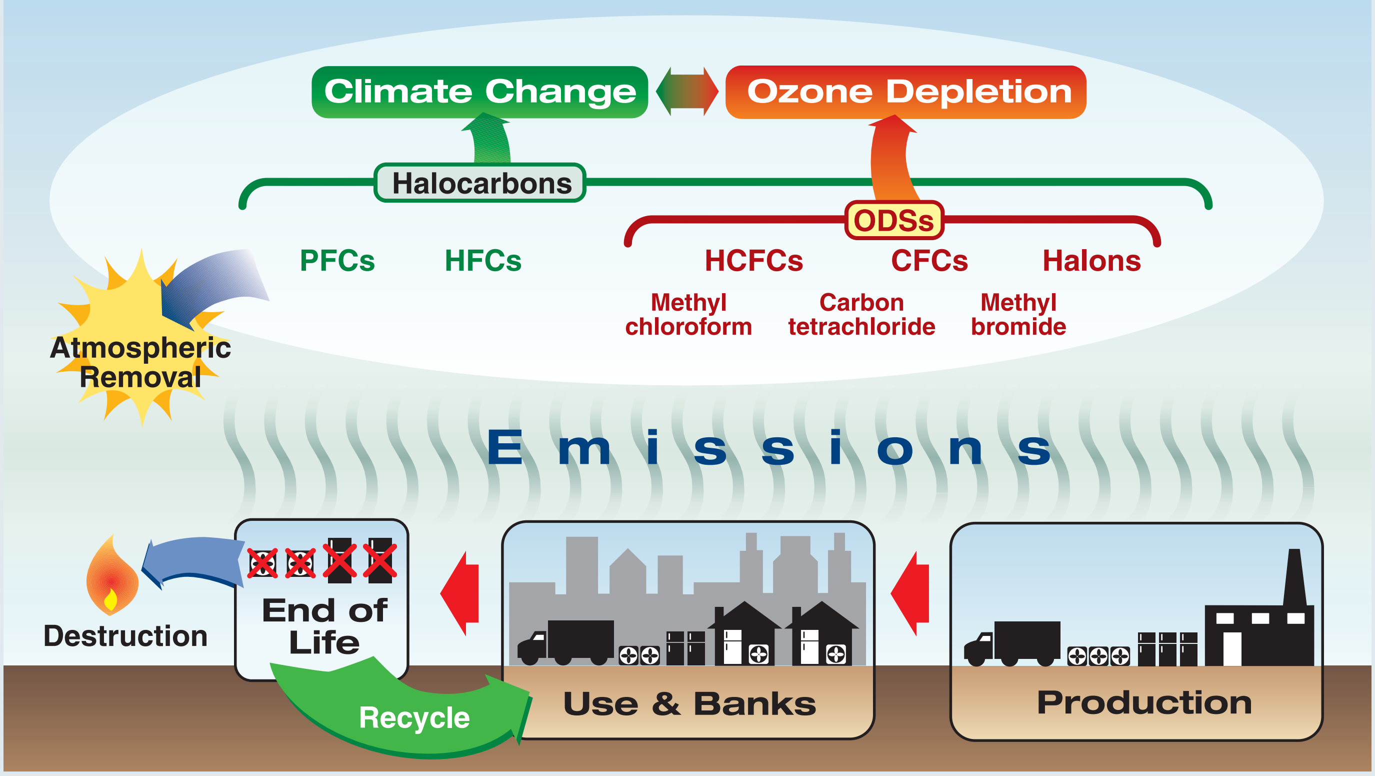


Figure SPM-1. Schematic diagram of major issues addressed by this report. Chlorofluorocarbons (CFCs), halons and hydrochlorofluorocarbons (HCFCs) contribute to ozone depletion and climate change, while hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) contribute only to climate change and are among possible non-ozone depleting alternatives for ODSs. Red denotes gases included under the Montreal Protocol and its amendments and adjustments[4] while green denotes those included under the UNFCCC and its Kyoto Protocol. Options considered in this report for reducing halocarbon emissions include improved containment, recovery, recycling, destruction of byproducts and existing banks[5], and use of alternative processes, or substances with reduced or negligible global warming potentials.

---

[1] Decision 12/CP.8, FCCC/CP/2002/7/Add.1, page 30.
[2] Decision XIV/10 UNEP/OzL.Pro.14/9, page 42.
[3] Ozone within this report refers to stratospheric ozone unless otherwise noted.
[4] Hereafter referred to as the Montreal Protocol.
[5] Banks are the total amount of substances contained in existing equipment, chemical stockpiles, foams and other products not yet released to the atmosphere.

are covered under the UNFCCC and its Kyoto Protocol. Options chosen to protect the ozone layer could influence climate change. Climate change may also indirectly influence the ozone layer.

This report considers the effects of total emissions of ODSs and their substitutes on the climate system and the ozone layer. In particular, this provides a context for understanding how replacement options could affect global warming. The report does not attempt to cover comprehensively the effect of replacement options on the ozone layer.

The report considers, by sector, options for reducing halocarbon emissions, options involving alternative substances, and technologies, to address greenhouse gas emissions reduction. It considers HFC and PFC emissions insofar as these relate to replacement of ODSs. HFC and PFC emissions from aluminum or semiconductor production or other sectors are not covered.

The major application sectors using ODSs and their HFC/PFC substitutes include refrigeration, air conditioning, foams, aerosols, fire protection and solvents. Emissions of these substances originate from manufacture and any unintended byproduct releases, intentionally emissive applications, evaporation and leakage from banks contained in equipment and products during use, testing and maintenance, and end-of-life practices.

With regard to specific emission reduction options, the report generally limits its coverage to the period up to 2015, for which reliable literature is available on replacement options with significant market potential for these rapidly evolving sectors. Technical performance, potential assessment methodologies and indirect emissions[6] related to energy use are considered, as well as costs, human health and safety, implications for air quality, and future availability issues.

---

[6] It should be noted that the National Inventory Reporting community uses the term 'indirect emissions' to refer specifically to those greenhouse gas emissions which arise from the breakdown of another substance in the environment. This is in contrast to the use of the term in this report, which specifically refers to energy-related CO_2 emissions associated with Life Cycle Assessment (LCA) approaches such as Total Equivalent Warming Impact (TEWI) or Life Cycle Climate Performance (LCCP).

2. Halocarbons, ozone depletion and climate change

2.1 What are the past and present effects of ODSs and their substitutes on the Earth's climate and the ozone layer?

Halocarbons, and in particular ODSs, have contributed to positive direct radiative forcing[7] and associated increases in global average surface temperature (see Figure SPM-2). The total positive direct radiative forcing due to increases in industrially produced ODS and non-ODS halocarbons from 1750 to 2000 is estimated to be 0.33 ± 0.03 W m^{-2}, representing about 13% of the total due to increases in all well-mixed greenhouse gases over that period. Most halocarbon increases have occurred in recent decades. Atmospheric concentrations of CFCs were stable or decreasing in the period 2001–2003 (0 to –3% per year, depending on the specific gas) while the halons and the substitute hydrochlorofluorocarbons (HCFCs) and HFCs increased (+1 to +3% per year, +3 to +7% per year, and +13 to +17% per year, respectively). [1.1, 1.2, 1.5 and 2.3][8]

Stratospheric ozone depletion observed since 1970 is caused primarily by increases in concentrations of reactive chlorine and bromine compounds that are produced by degradation of anthropogenic ODSs, including halons, CFCs, HCFCs, methyl chloroform (CH_3CCl_3), carbon tetrachloride (CCl_4) and methyl bromide (CH_3Br). [1.3 and 1.4]

Ozone depletion produces a negative radiative forcing of climate, which is an indirect cooling effect of the ODSs (see Figure SPM-2). Changes in ozone are believed to currently contribute a globally averaged radiative forcing of about –0.15 ± 0.10 W m^{-2}. The large uncertainty in the indirect radiative forcing of ODSs arises mainly because of uncertainties in the detailed vertical distribution of ozone depletion. This negative radiative forcing is *very likely*[10] to be smaller than the positive direct radiative forcing due to ODSs alone (0.32 ± 0.03 W m^{-2}). [1.1, 1.2 and 1.5]

Warming due to ODSs and cooling associated with ozone depletion are two distinct climate forcing mechanisms that do not simply offset one another. The spatial and seasonal distributions of the cooling effect of ozone depletion differ from those of the warming effect. A limited number of global climate modelling and statistical studies suggest that ozone depletion is one mechanism that may affect patterns of climate variability which are important for tropospheric circulation and temperatures in both hemispheres. However, observed changes in these patterns of variability cannot be unambiguously attributed to ozone depletion. [1.3 and 1.5]

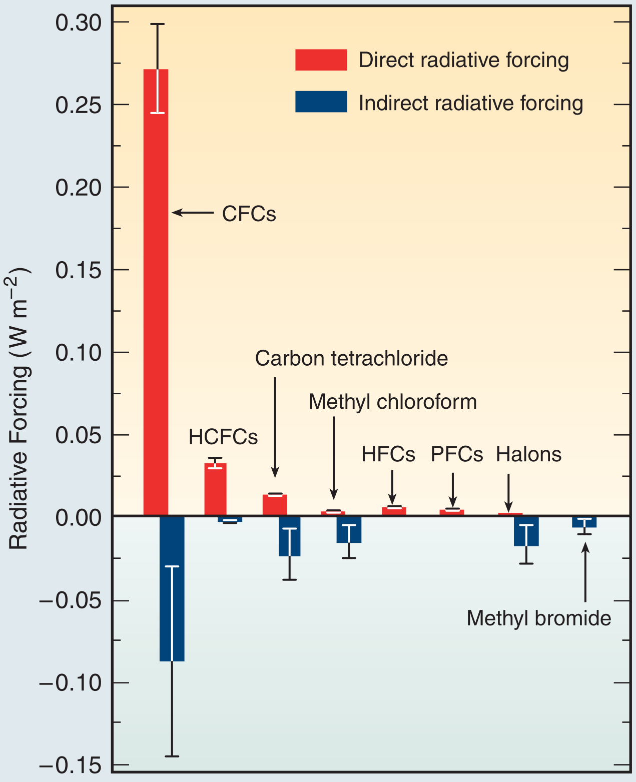


Figure SPM-2. Direct and indirect radiative forcing (RF) due to changes in halocarbons from 1750 to 2000.[9] Error bars denote ±2 standard-deviation uncertainties. [Based on Table 1.1]

---

[7] Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, and is an index of the importance of the factor as a potential climate change mechanism. It is expressed in watts per square meter (W m^{-2}). A greenhouse gas causes direct radiative forcing through absorption and emission of radiation and may cause indirect radiative forcing through chemical interactions that influence other greenhouse gases or particles.

[8] Numbers in square brackets indicate the sections in the main report where the underlying material and references for the paragraph can be found.

[9] PFCs used as substitutes for ODSs make only a small contribution to the total PFC radiative forcing.

[10] In this Summary for Policymakers, the following words have been used where appropriate to indicate judgmental estimates of confidence: very likely (90–99% chance); *likely* (66–90% chance); *unlikely* (10–33% chance); and *very unlikely* (1–10% chance).

Each type of gas has had different greenhouse warming and ozone depletion effects (see Figure SPM-2) depending mainly on its historic emissions, effectiveness as a greenhouse gas, lifetime and the amount of chlorine and/or bromine in each molecule. Bromine-containing gases currently contribute much more to cooling than to warming, whereas CFCs and HCFCs contribute more to warming than to cooling. HFCs and PFCs contribute only to warming. [1.5 and 2.5]

2.2 How does the phase-out of ODSs affect efforts to address climate change and ozone depletion?

Actions taken under the Montreal Protocol have led to the replacement of CFCs with HCFCs, HFCs, and other substances and processes. Because replacement species generally have lower global warming potentials[11] (GWPs), and because total halocarbon emissions have decreased, their combined CO_2-equivalent (direct GWP-weighted) emission has been reduced. The combined CO_2-equivalent emissions of CFCs, HCFCs and HFCs derived from atmospheric observations decreased from about 7.5 ± 0.4 $GtCO_2$-eq per year around 1990 to 2.5 ± 0.2 $GtCO_2$-eq per year around 2000, equivalent to about 33% and 10%, respectively, of the annual CO_2 emissions due to global fossil fuel burning. Stratospheric chlorine levels have approximately stabilized and may have already started to decline. [1.2, 2.3 and 2.5]

Ammonia and those hydrocarbons (HCs) used as halocarbon substitutes have atmospheric lifetimes ranging from days to months, and the direct and indirect radiative forcings associated with their use as substitutes are *very likely* to have a negligible effect on global climate. Changes in energy-related emissions associated with their use may also need to be considered. (See Section 4 for treatment of comprehensive assessment of ODS replacement options.) [2.5]

Based on the Business-As-Usual scenario developed in this report, the estimated direct radiative forcing of HFCs in 2015 is about 0.030 W m^{-2}; based on scenarios from the IPCC Special Report on Emission Scenarios (SRES), the radiative forcing of PFCs[9] in 2015 is about 0.006 W m^{-2}. Those HFC and PFC radiative forcings correspond to about 1.0% and 0.2%, respectively, of the estimated radiative forcing of all well-mixed greenhouse gases in 2015, with the contribution of ODSs being about 10%. While this report particularly focused on scenarios for the period up to 2015, for the period beyond 2015 the IPCC SRES scenarios were considered but were not re-assessed. These SRES scenarios project significant growth in radiative forcing from HFCs over the following decades, but the estimates are likely to be very uncertain due to growing uncertainties in technological practices and policies. [1.5, 2.5 and 11.5]

Observations and model calculations suggest that the global average amount of ozone depletion has now approximately stabilized (for example, see Figure SPM-3). Although considerable variability in ozone is expected from year to year, including in polar regions where depletion is largest, the ozone layer is expected to begin to recover in coming decades due to declining ODS concentrations, assuming full compliance with the Montreal Protocol. [1.2 and 1.4]

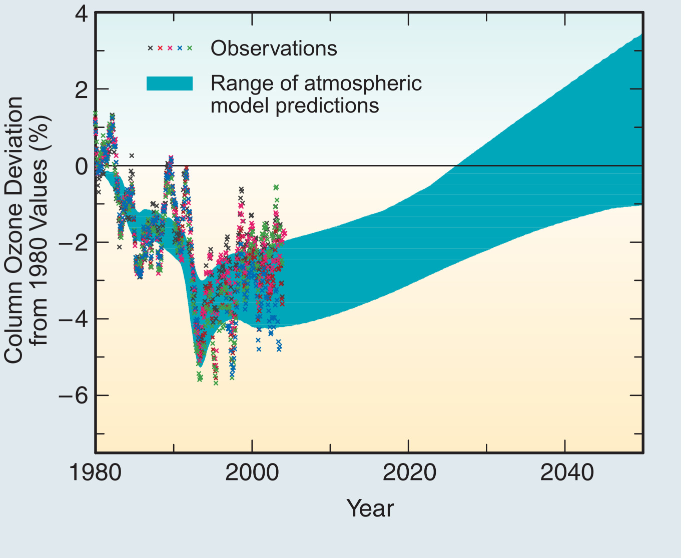


Figure SPM-3. Observed and modelled low- and mid-latitude (60ºS–60ºN) column ozone amounts as percent deviations from the 1980 values. [Box 1.7]

---

[11] GWPs are indices comparing the climate impact of a pulse emission of a greenhouse gas relative to that of emitting the same amount of CO_2, integrated over a fixed time horizon.

Over the long term, projected increases in other greenhouse gases could increasingly influence the ozone layer by cooling the stratosphere and changing stratospheric circulation. As a result of the cooling effect and of reducing ODS concentrations, ozone is *likely* to increase over much of the stratosphere, but could decrease in some regions, including the Arctic. However, the effects of changes in atmospheric circulation associated with climate change could be larger than these factors, and the net impact on total ozone due to increases in atmospheric concentrations of greenhouse gases is currently uncertain in both magnitude and sign. Based on current models an Arctic 'ozone hole' similar to that presently observed over the Antarctic is *very unlikely* to occur. [1.4]

The relative future warming and cooling effects of emissions of CFCs, HCFCs, HFCs, PFCs and halons vary with gas lifetimes, chemical properties and time of emission (see Table SPM-1). The atmospheric lifetimes range from about a year to two decades for most HFCs and HCFCs, decades to centuries for some HFCs and most halons and CFCs, and 1000 to 50,000 years for PFCs. Direct GWPs for halocarbons range from 5 to over 10,000. ODS indirect cooling is projected to cease upon ozone layer recovery, so that GWPs associated with the indirect cooling effect depend on the year of emission, compliance with the Montreal Protocol and gas lifetimes. These indirect GWPs are subject to much greater uncertainties than direct GWPs. [1.5, 2.2 and 2.5]

2.3 What are the implications of substitution of ODSs for air quality and other environmental issues relating to atmospheric chemistry?

Substitution for ODSs in air conditioning, refrigeration, and foam blowing by HFCs, PFCs, and other gases such as hydrocarbons are not expected to have a significant effect on global tropospheric chemistry. Small but not negligible impacts on air quality could occur near localized emission sources and such impacts may be of some concern, for instance in areas that currently fail to meet local standards. [2.4 and 2.6]

Persistent degradation products (such as trifluoroacetic acid, TFA) of HFCs and HCFCs are removed from the atmosphere via deposition and washout processes. However, existing environmental risk assessment and monitoring studies indicate that these are not expected to result in environmental concentrations capable of causing significant ecosystem damage. Measurements of TFA in sea water indicate that the anthropogenic sources of TFA are smaller than natural sources, but the natural sources are not fully identified. [2.4]

Table SPM-1. GWPs of halocarbons commonly reported under the Montreal Protocol and the UNFCCC and its Kyoto Protocol and assessed in this report relative to CO_2, for a 100-year time horizon, together with their lifetimes and GWPs used for reporting under the UNFCCC. Gases shown in blue (darker shading) are covered under the Montreal Protocol and gases shown in yellow (lighter shading) are covered under the UNFCCC. [Tables 2.6 and 2.7]

Gas	GWP for direct radiative forcing[a]	GWP for indirect radiative forcing (Emission in 2005[b])	Lifetime (years)	UNFCCC Reporting GWP[c]
CFCs				
CFC-12	10,720 ± 3750	–1920 ± 1630	100	n.a.[d]
CFC-114	9880 ± 3460	Not available	300	n.a.[d]
CFC-115	7250 ± 2540	Not available	1700	n.a.[d]
CFC-113	6030 ± 2110	–2250 ± 1890	85	n.a.[d]
CFC-11	4680 ± 1640	–3420 ± 2710	45	n.a.[d]
HCFCs				
HCFC-142b	2270 ± 800	–337 ± 237	17.9	n.a.[d]
HCFC-22	1780 ± 620	–269 ± 183	12	n.a.[d]
HCFC-141b	713 ± 250	–631 ± 424	9.3	n.a.[d]
HCFC-124	599 ± 210	–114 ± 76	5.8	n.a.[d]
HCFC-225cb	586 ± 205	–148 ± 98	5.8	n.a.[d]
HCFC-225ca	120 ± 42	–91 ± 60	1.9	n.a.[d]
HCFC-123	76 ± 27	–82 ± 55	1.3	n.a.[d]
HFCs				
HFC-23	14,310 ± 5000	~0	270	11,700
HFC-143a	4400 ± 1540	~0	52	3800
HFC-125	3450 ± 1210	~0	29	2800
HFC-227ea	3140 ± 1100	~0	34.2	2900
HFC-43-10mee	1610 ± 560	~0	15.9	1300
HFC-134a	1410 ± 490	~0	14	1300
HFC-245fa	1020 ± 360	~0	7.6	–[e]
HFC-365mfc	782 ± 270	~0	8.6	–[e]
HFC-32	670 ± 240	~0	4.9	650
HFC-152a	122 ± 43	~0	1.4	140
PFCs				
C_2F_6	12,010 ± 4200	~0	10,000	9200
C_6F_{14}	9140 ± 3200	~0	3200	7400
CF_4	5820 ± 2040	~0	50,000	6500
Halons				
Halon-1301	7030 ± 2460	–32,900 ± 27,100	65	n.a.[d]
Halon-1211	1860 ± 650	–28,200 ± 19,600	16	n.a.[d]
Halon-2402	1620 ± 570	–43,100 ± 30,800	20	n.a.[d]
Other Halocarbons				
Carbon tetrachloride (CCl_4)	1380 ± 480	–3330 ± 2460	26	n.a.[d]
Methyl chloroform (CH_3CCl_3)	144 ± 50	–610 ± 407	5.0	n.a.[d]
Methyl bromide (CH_3Br)	5 ± 2	–1610 ± 1070	0.7	n.a.[d]

[a] Uncertainties in GWPs for direct positive radiative forcing are taken to be ±35% (2 standard deviations) (IPCC, 2001).

[b] Uncertainties in GWPs for indirect negative radiative forcing consider estimated uncertainty in the time of recovery of the ozone layer as well as uncertainty in the negative radiative forcing due to ozone depletion.

[c] The UNFCCC reporting guidelines use GWP values from the IPCC Second Assessment Report (see FCCC/SBSTA/2004/8, http://unfccc.int/resource/docs/2004/sbsta/08.pdf).

[d] ODSs are not covered under the UNFCCC.

[e] The IPCC Second Assessment Report does not contain GWP values for HFC-245fa and HFC-365mfc. However, the UNFCCC reporting guidelines contain provisions relating to the reporting of emissions from all greenhouse gases for which IPCC-assessed GWP values exist.

3. Production, banks and emissions

3.1 How are production, banks and emissions related in any particular year?

Current emissions of ODSs and their substitutes are largely determined by historic use patterns. For CFCs and HCFCs, a significant contribution (now and in coming decades) comes from their respective banks. There are no regulatory obligations to restrict these CFC and HCFC emissions either under the Montreal Protocol or the UNFCCC and its Kyoto Protocol, although some countries have effective national policies for this purpose.

Banks are the total amount of substances contained in existing equipment, chemical stockpiles, foams and other products not yet released to the atmosphere (see Figure SPM-1). The build-up of banks of (relatively) new applications of HFCs will – in the absence of additional bank management measures – also significantly determine post 2015 emissions.

3.2 What can observations of atmospheric concentrations tell us about banks and emissions?

Observations of atmospheric concentrations, combined with production and use pattern data, can indicate the significance of banks, but not their exact sizes.

The most accurate estimates of emissions of CFC-11 and CFC-12 are derived from observations of atmospheric concentrations. Those emissions are now larger than estimated releases related to current production, indicating that a substantial fraction of these emissions come from banks built up through past production. Observations of atmospheric concentrations show that global emissions of HFC-134a are presently smaller than reported production, implying that this bank is growing. The total global amount of HFC-134a currently in the atmosphere is believed to be about equal to the amount in banks. [2.5 and 11.3.4]

In the case of CFC-11 and some other gases, the lack of information on use patterns makes it difficult to assess the contribution to observed emissions from current production and use. Further work in this area is required to clarify the sources.

3.3 How are estimated banks and emissions projected to develop in the period 2002 to 2015?

Banks of CFCs, HCFCs, HFCs and PFCs were estimated at about 21 GtCO$_2$-eq in 2002[12,13]. In a Business-As-Usual (BAU) scenario, banks are projected to decline to about 18 GtCO$_2$-eq in 2015[14]. [7, 11.3 and 11.5]

In 2002, CFC, HCFC and HFC banks were about 16, 4 and 1 GtCO$_2$-eq (direct GWP weighted), respectively (see Figure SPM-4). In 2015, the banks are about 8, 5 and 5 GtCO$_2$-eq, respectively, in the BAU scenario. Banks of PFCs used as ODS replacements were about 0.005 GtCO$_2$-eq in 2002.

CFC banks associated with refrigeration, stationary air-conditioning (SAC)[15] and mobile air-conditioning (MAC) equipment are projected to decrease from about 6 to 1 GtCO$_2$-eq over the period 2002 to 2015, mainly due to release to the atmosphere and partly due to end-of-life recovery and destruction. CFC banks in foams are projected to decrease much more slowly over the same period (from 10 to 7 GtCO$_2$-eq), reflecting the much slower release of banked blowing agents from foams when compared with similarly sized banks of refrigerant in the refrigeration and air-conditioning sector.

HFC banks have started to build up and are projected to reach about 5 GtCO$_2$-eq in 2015. Of these, HFCs banked in foams represent only 0.6 GtCO$_2$-eq, but are projected to increase further after 2015.

---

[12] Greenhouse gas (GHG) emissions and banks expressed in terms of CO$_2$-equivalents use GWPs for direct radiative forcing for a 100-year time horizon. Unless stated otherwise, the most recent scientific values for the GWPs are used, as assessed in this report and as presented in Table SPM-1 (Column for 'GWP for direct radiative forcing').

[13] Halons cause much larger negative indirect than positive direct radiative forcing and, in the interest of clarity, their effects are not given here.

[14] In the BAU projections, it is assumed that all existing measures continue, including Montreal Protocol (phase-out) and relevant national policies. The current trends in practices, penetration of alternatives, and emission factors are maintained up to 2015. End-of-life recovery efficiency is assumed not to increase.

[15] In this Summary for Policymakers the 'refrigeration' sector comprises domestic, commercial, industrial (including food processing and cold storage) and transportation refrigeration. [4] 'Stationary air conditioning (SAC)' comprises residential and commercial air conditioning and heating. [5] 'Mobile air conditioning (MAC)' applies to cars, buses and passenger compartments of trucks.

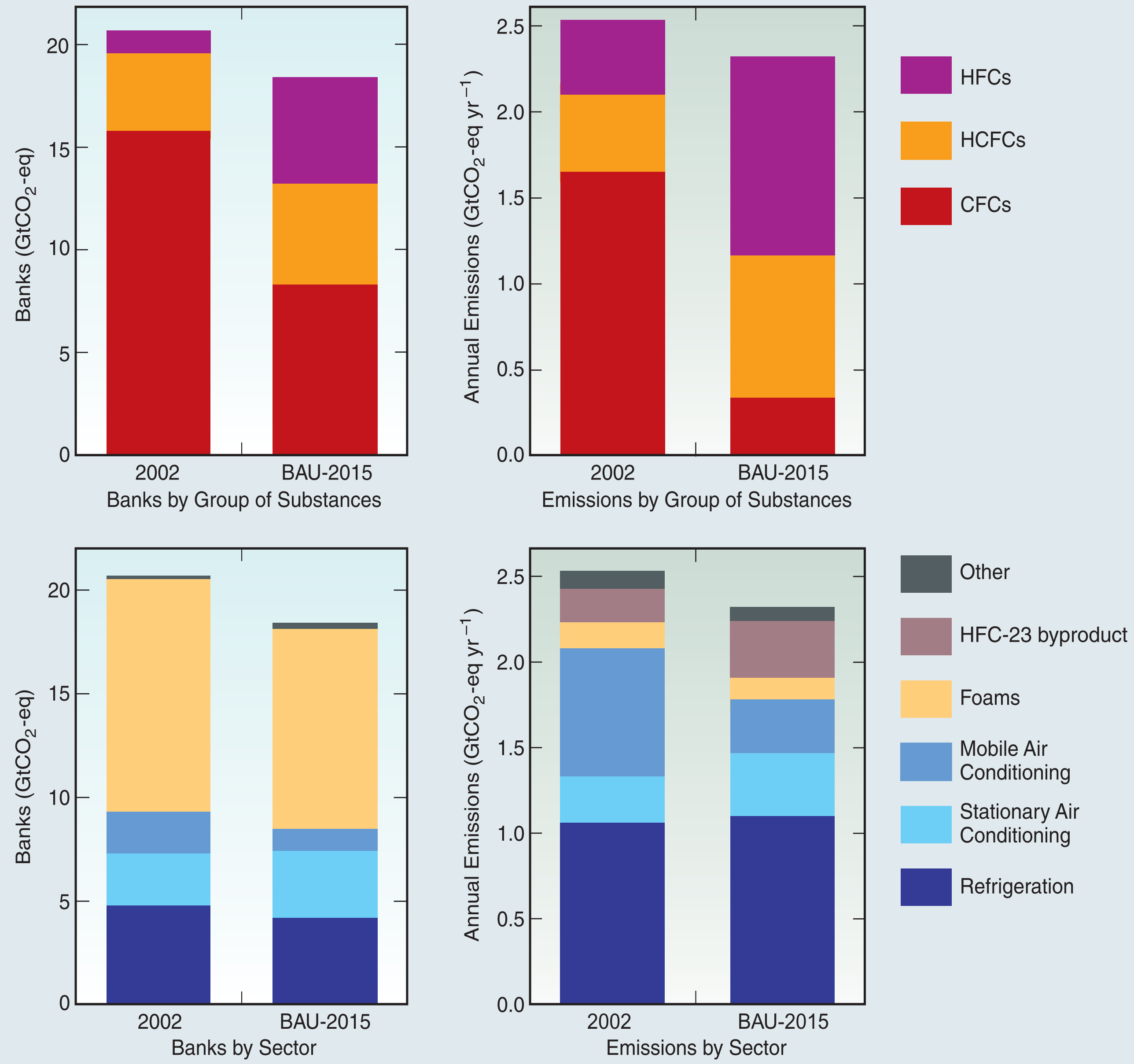


Figure SPM-4. Historic data for 2002 and Business-As-Usual (BAU) projections for 2015 of greenhouse gas CO_2-equivalent banks (left) and direct annual emissions (right), related to the use of CFCs, HCFCs and HFCs. Breakdown per group of greenhouse gases (top) and per emission sector (bottom). 'Other' includes Medical Aerosols, Fire Protection, Non-Medical Aerosols and Solvents. [11.3 and 11.5]

In the BAU scenario, total direct emissions of CFCs, HCFCs, HFCs and PFCs are projected to represent about 2.3 $GtCO_2$-eq per year by 2015 (as compared to about 2.5 $GtCO_2$-eq per year in 2002). CFC and HCFC emissions are together decreasing from 2.1 (2002) to 1.2 $GtCO_2$-eq per year (2015), and emissions of HFCs are increasing from 0.4 (2002) to 1.2 $GtCO_2$-eq per year (2015)[16]. PFC emissions from ODS substitute use are about 0.001 $GtCO_2$-eq per year (2002) and projected to decrease. [11.3 and 11.5]

Figure SPM-4 shows the relative contribution of sectors to global direct greenhouse gas (GHG) emissions that are related to the use of ODSs and their substitutes. Refrigeration applications together with SAC and MAC contribute the bulk of global direct GHG emissions in line with the higher emission rates associated with refrigerant banks. The largest part of GHG emissions from foams is expected to occur after 2015 because most releases occur at end-of-life.

With little new production, total CFC banks will decrease due to release to the atmosphere during operation and disposal. In the absence of additional measures a significant part of the CFC banks will have been emitted by 2015. Consequently, annual CFC emissions are projected to decrease from 1.7 (2002) to 0.3 $GtCO_2$-eq per year (2015).

HCFC emissions are projected to increase from 0.4 (2002) to 0.8 $GtCO_2$-eq per year (2015), owing to a steep increase expected for their use in (commercial) refrigeration and SAC applications.

The projected threefold increase in HFC emissions is the result of increased application of HFCs in the refrigeration, SAC and MAC sectors, and due to byproduct emissions of HFC-23 from increased HCFC-22 production (from 195 $MtCO_2$-eq per year in 2002 to 330 $MtCO_2$-eq per year in 2015 BAU).

Uncertainties in emission estimates are significant. Comparison of results of atmospheric measurements with inventory calculations shows differences per group of substances in the order of 10 to 25%. For individual gases the differences can be much bigger. This is caused by unidentified emissive applications of some substances, not accounted for in inventory calculations, and uncertainties in the geographically distributed datasets of equipment in use. [11.3.4]

The literature does not allow for an estimate of overall indirect[6] GHG emissions related to energy consumption. For individual applications, the relevance of indirect GHG emissions over a life cycle can range from low to high, and for certain applications may be up to an order of magnitude larger than direct GHG emissions. This is highly dependent on the specific sector and product/application characteristics, the carbon-intensity of the consumed electricity and fuels during the complete life cycle of the application, containment during the use-phase, and the end-of-life treatment of the banked substances. [3.2, 4 and 5]

---

[16] For these emission values the most recent scientific values for GWPs are used (see Table SPM-1, second column, 'GWP for direct radiative forcing'). If the UNFCCC GWPs would be used (Table SPM-1, last column, 'UNFCCC Reporting GWP'), reported HFC emissions (expressed in tonnes of CO_2-eq) would be about 15% lower.

4. Options for ODS phase-out and reducing greenhouse gas emissions

4.1 What major opportunities have been identified for reductions of greenhouse gas emissions and how can they be assessed?

Reductions in direct GHG emissions are available for all sectors discussed in this report and can be achieved through:

- **improved containment of substances;**
- **reduced charge of substances in equipment;**
- **end-of-life recovery and recycling or destruction of substances;**
- **increased use of alternative substances with a reduced or negligible global warming potential; and**
- **not-in-kind technologies[17].**

A comprehensive assessment would cover both direct emissions and indirect energy-related emissions, full life-cycle aspects, as well as health, safety and environmental considerations. However, due to limited availability of published data and comparative analyses, such comprehensive assessments are currently almost absent.

Methods for determining which technology option has the highest GHG emission reduction potential address both direct emissions of halocarbons or substitutes and indirect energy-related emissions over the full life cycle. In addition, comprehensive methods[18] assess a wide range of environmental impacts. Other, simplified methods[19] exist to assess life-cycle impacts and commonly provide useful indicators for life-cycle greenhouse gas emissions of an application. Relatively few transparent comparisons applying these methods have been published. The conclusions from these comparisons are sensitive to assumptions about application-specific, and often region- and time-specific parameters (e.g., site-specific situation, prevailing climate, energy system characteristics). [3.5]

Comparative economic analyses are important to identify cost-effective reduction options. However, they require a common set of methods and assumptions (e.g., costing methodology, time-frame, discount rate, future economic conditions, system boundaries). The development of simplified standardized methodologies would enable better comparisons in the future. [3.3]

The risks of health and safety impacts can be assessed in most cases using standardized methods. [3.4 and 3.5]

GHG emissions related to energy consumption can be significant over the lifetime of appliances considered in this report. Energy efficiency improvements can thus lead to reductions in indirect emissions from these appliances, depending on the particular energy source used and other circumstances, and produce net cost reductions, particularly where the use-phase of the application is long (e.g., in refrigeration and SAC).
The assessed literature did not allow for a global estimate of this reduction potential, although several case studies at technology and country level illustrate this point.

Through application of current best practices[20] and recovery methods, there is potential to halve (1.2 $GtCO_2$-eq per year reduction) the BAU direct emissions from ODSs and their GHG substitutes by 2015[21]. About 60% of this potential concerns HFC emissions, 30% HCFCs and 10% CFCs.
The estimates are based on a Mitigation Scenario[22] which makes regionally differentiated assumptions on best practices in production, use, substitution, recovery and destruction of these substances. Sectoral contributions are shown in Figure SPM-5. [11.5]

---

[17] Not-in-kind technologies achieve the same product objective without the use of halocarbons, typically with an alternative approach or unconventional technique. Examples include the use of stick or spray pump deodorants to replace CFC-12 aerosol deodorants; the use of mineral wool to replace CFC, HFC or HCFC insulating foam; and the use of dry powder inhalers (DPIs) to replace CFC or HFC metered dose inhalers (MDIs).

[18] Comprehensive methods, e.g. Life Cycle Assessment (LCA), cover all phases of the life cycle for a number of environmental impact categories. The respective methodologies are detailed in international ISO standards ISO 14040:1997, ISO 14041:1998, ISO 14042:2000, and ISO 14043:2000.

[19] Typical simplified methods include Total Equivalent Warming Impact (TEWI), which assesses direct and indirect greenhouse emissions connected only with the use-phase and disposal; and Life Cycle Climate Performance (LCCP), which also includes direct and indirect greenhouse emissions from the manufacture of the active substances.

[20] For this Report, best practice is considered the lowest achievable value of halocarbon emission at a given date, using commercially proven technologies in the production, use, substitution, recovery and destruction of halocarbon or halocarbon-based products (for specific numbers, see Table TS-6).

[21] For comparison, CO_2 emissions related to fossil fuel combustion and cement production were about 24 $GtCO_2$ per year in 2000.

[22] The Mitigation Scenario used in this Report, projects the future up to 2015 for the reduction of halocarbon emissions, based on regionally differentiated assumptions of best practices.

Of the bank-related emissions that can be prevented in the period until 2015, the bulk is in refrigerant-based applications where business-as-usual emission rates are considerably more significant than they are for foams during the period in question. With earlier action, such as recovery/destruction and improved containment, more of the emissions from CFC banks can be captured.

4.2 What are the sectoral emission reduction potentials in 2015 and what are associated costs?

In refrigeration applications direct GHG emissions can be reduced by 10% to 30%. For the refrigeration sector as a whole, the Mitigation Scenario shows an overall direct emission reduction of about 490 $MtCO_2$-eq per year by 2015, with about 400 $MtCO_2$-eq per year predicted for commercial refrigeration. Specific costs are in the range of 10 to 300 US\$/tCO_2-eq[23,24]. Improved system energy efficiencies can also significantly reduce indirect GHG emissions.

In full supermarket systems, up to 60% lower LCCP[19] values can be obtained by using alternative refrigerants, improved containment, distributed systems, indirect systems or cascade systems. Refrigerant specific emission abatement costs range for the commercial refrigeration sector from 20 to 280 US\$/tCO_2-eq**.**

In food processing, cold storage and industrial refrigeration, ammonia is forecast for increased use in the future, with HFCs replacing HCFC-22 and CFCs. Industrial refrigeration refrigerant specific emissions abatement costs were determined to be in the range from 27 to 37 US/tCO_2-eq. In transport refrigeration, lower GWP alternatives, such as ammonia, hydrocarbons and ammonia/carbon dioxide have been commercialized.

The emission reduction potential in domestic refrigeration is relatively small, with specific costs in the range of 0 to 130 US\$/tCO_2-eq. Indirect emissions of systems using either HFC-134a or HC-600a (isobutane) dominate total emissions, for different carbon intensities of electric power generation. The difference between the LCCP[19] of HFC-134a and isobutane systems is small and end-of-life recovery, at a

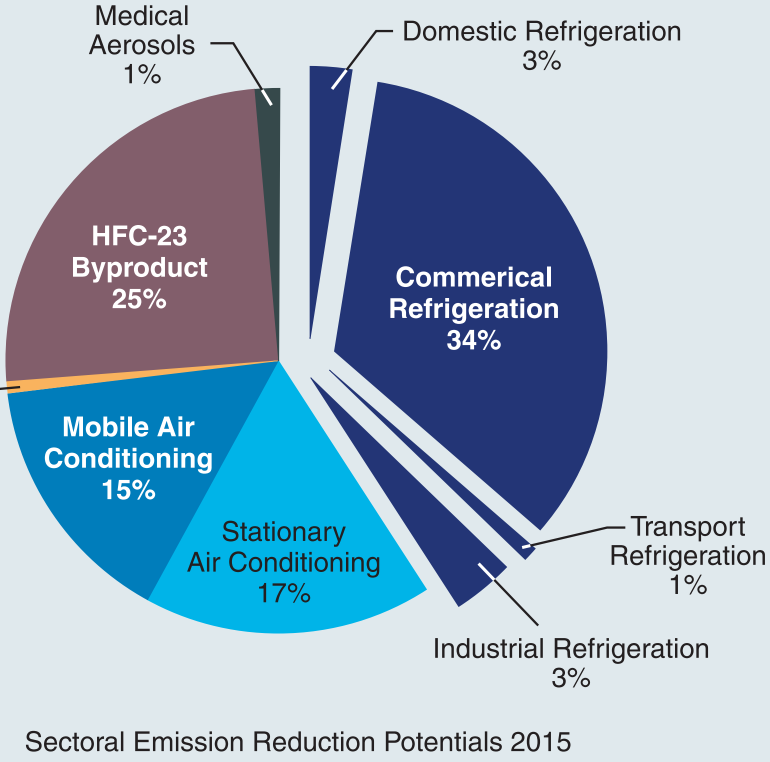


Figure SPM-5. Sectoral reduction potentials for direct emissions of CFCs, HCFCs and HFCs in 2015 as compared to the BAU projections. The overall reduction potential is about half (1.2 $GtCO_2$-eq per year) of the BAU direct GHG emissions.

---

[23] The presented cost data concern direct emission reductions only. Taking into account energy efficiency improvements may result in even net negative specific costs (savings).

[24] Costs in this report are given in 2002 US dollars unless otherwise stated.

certain cost increase, can further reduce the magnitude of the difference. [4]

Direct GHG emissions of residential and commercial air-conditioning and heating equipment (SAC) can be reduced by about 200 $MtCO_2$-eq per year by 2015 relative to the BAU scenario. Specific costs range from –3 to 170 US$/$tCO_2$-eq[23]. When combined with improvements in system energy efficiencies, which reduce indirect GHG emissions, in many cases net financial benefits accrue. Opportunities to reduce direct GHG (i.e., refrigerant) emissions can be found in (i) more efficient recovery of refrigerant at end-of-life (in the Mitigation Scenario assumed to be 50% and 80% for developing and developed countries, respectively); (ii) refrigerant charge reduction (up to 20%); (iii) better containment and (iv) the use of refrigerants with reduced or negligible GWPs in suitable applications.

Improving the integrity of the building envelope (reduced heat gain or loss) can have a significant impact on indirect emissions.

HFC mixtures and hydrocarbons (HCs) (for small systems) are used as alternatives for HCFC-22 in developed countries. For those applications where HCs can be safely applied, the energy efficiency is comparable to fluorocarbon refrigerants. Future technical developments could reduce refrigerant charge, expanding the applicability of HCs. [5]

In mobile air conditioning, a reduction potential of 180 $MtCO_2$-eq per year by 2015 could be achieved at a cost of 20 to 250 US$/$tCO_2$-eq[23]. Specific costs differ per region and per solution.
Improved containment, and end-of-life recovery (both of CFC-12 and HFC-134a) and recycling (of HFC-134a) could reduce direct GHG emissions by up to 50%, and total (direct and indirect) GHG emissions of the MAC unit by 30 to 40% at a financial benefit to vehicle owners. New systems with either CO_2 or HFC-152a, with equivalent LCCP, are likely to enter the market, leading to total GHG system emission reductions estimated at 50 to 70% in 2015 at an estimated added specific cost of 50 to 180 US$ per vehicle.

Hydrocarbons and hydrocarbon blends, which have been used to a limited extent, present suitable thermodynamic properties and permit high energy efficiency. However, the safety and liability concerns identified by vehicle manufacturers and suppliers limit the possible use of hydrocarbons in new vehicles. [6.4.4]

Due to the long life-span of most foam applications, by 2015 a limited emission reduction of 15 to 20 $MtCO_2$-eq per year is projected at specific costs ranging from 10 to 100 US$/$tCO_2$-eq[23]. The potential for emission reduction increases in following decades.
Several short-term emission reduction steps, such as the planned elimination of HFC use in emissive one-component foams in Europe, are already in progress and are considered as part of the BAU. Two further key areas of potential emission reduction exist in the foams sector. The first is a potential reduction in halocarbon use in newly manufactured foams. However, the enhanced use of blends and the further phase-out of fluorocarbon use both depend on further technology development and market acceptance. Actions to reduce HFC use by 50% between 2010 and 2015, would result in emission reduction of about 10 $MtCO_2$-eq per year, at a specific cost of 15 to 100 US$/$tCO_2$-eq, with further reductions thereafter[23].

The second opportunity for emission reduction can be found in the worldwide banks of halocarbons contained in insulating foams in existing buildings and appliances (about 9 and 1 $GtCO_2$-eq for CFC and HCFC, respectively in 2002). Although recovery effectiveness is yet to be proven, and there is little experience to date, particularly in the buildings sector, commercial operations are already recovering halocarbons from appliances at 10 to 50 US$/$tCO_2$-eq[23]. Emission reductions may be about 7 $MtCO_2$-eq per year in 2015. However, this potential could increase significantly in the period between 2030 and 2050, when large quantities of building insulation foams will be decommissioned. [7]

The reduction potential for medical aerosols is limited due to medical constraints, the relatively low emission level and the higher costs of alternatives. The major contribution (14 $MtCO_2$-eq per year by 2015 compared to a BAU emission of 40 $MtCO_2$-eq per year) to a reduction of GHG emissions for metered dose inhalers (MDIs) would be the completion of the transition from CFC to HFC MDIs beyond what was already assumed as BAU. The health and safety of the patient is considered to be of paramount importance in treatment decisions, and there are significant medical constraints to limit the use of HFC MDIs. If salbutamol MDIs (approximately 50% of total MDIs) would be replaced by dry powder inhalers (which is not assumed in the Mitigation Scenario) this would result in an annual emission reduction of about 10 $MtCO_2$-eq per year by 2015 at projected costs in the range of 150 to 300 US$/$tCO_2$-eq. [8]

In fire protection, the reduction potential by 2015 is small due to the relatively low emission level, the significant shifts to not-in-kind alternatives in the past and the lengthy procedures for introducing new equipment.
Direct GHG emissions for the sector are estimated at about 5 $MtCO_2$-eq per year in 2015 (BAU). Seventy five percent of original halon use has been shifted to agents with no climate impact. Four percent of the original halon applications continue to employ halons. The remaining 21% has been

shifted to HFCs with a small number of applications shifted to HCFCs and to PFCs. PFCs are no longer needed for new fixed systems and are limited to use as a propellant in one manufacturer's portable extinguisher agent blend. Due to the lengthy process of testing, approval and market acceptance of new fire protection equipment types and agents, no additional options will likely have appreciable impact by 2015. With the introduction of a fluoroketone (FK) in 2002, additional reductions at an increased cost are possible in this sector through 2015. Currently those reductions are estimated to be small compared to other sectors. [9]

For non-medical aerosols and solvents there are several reduction opportunities, but the reduction potentials are likely to be rather small because most remaining uses are critical to performance or safety. The projected BAU emissions by 2015 for solvents and aerosols are about 14 and 23 $MtCO_2$-eq per year, respectively. Substitution of HFC-134a by HFC-152a in technical aerosol dusters is a leading option for reducing GHG emissions. For contact cleaners and plastic casting mould release agents, the substitution of HCFCs by hydrofluoroethers (HFEs) and HFCs with lower GWPs offers an opportunity. Some countries have banned HFC use in cosmetic, convenience and novelty aerosol products, although HFC-134a continues to be used in many countries for safety reasons.

A variety of organic solvents can replace HFCs, PFCs and ODSs in many applications. These alternative fluids include lower GWP compounds such as traditional chlorinated solvents, HFEs, HCs and oxygenated solvents. Many not-in-kind technologies, including no-clean and aqueous cleaning processes, are also viable alternatives. [10]

Destruction of byproduct emissions of HFC-23 from HCFC-22 production has a reduction potential of up to 300 $MtCO_2$-eq per year by 2015 and specific costs below 0.2 US$/$tCO_2$-eq according to two European studies in 2000.
Reduction of HCFC-22 production due to market forces or national policies, or improvements in facility design and construction also could reduce HFC-23 emissions. [10.4]

4.3 What are the current policies, measures and instruments?

A variety of policies, measures and instruments have been implemented in reducing the use or emissions of ODSs and their substitutes, such as HFCs and PFCs. These include regulations, economic instruments, voluntary agreements and international cooperation. Furthermore, general energy or climate policies affect the indirect GHG emissions of applications with ODSs, their substitutes, or not-in-kind alternatives.

This report contains information on policies and approaches in place in some countries (mainly developed) for reducing the use or emissions of ODSs and their substitutes. Those relevant policies and approaches include:
- Regulations (e.g., performance standards, certification, restrictions, end-of-life management)
- Economic instruments (e.g., taxation, emissions trading, financial incentives and deposit refunds)
- Voluntary agreements (e.g., voluntary reductions in use and emissions, industry partnerships and implementation of good practice guidelines)
- International cooperation (e.g., Clean Development Mechanism)

It should be noted that policy considerations are dependent on specific applications, national circumstances and other factors.

4.4 What can be said about availability of HFCs/PFCs in the future for use in developing countries?

No published data are available to project future production capacity. However, as there are no technical or legal limits to HFC and PFC production, it can be assumed that the global production capacity will generally continue to satisfy or exceed demand. Future production is therefore estimated in this report by aggregating sectoral demand.

In the BAU scenario, global production capacity is expected to expand with additions taking place mainly in developing countries and through joint ventures. Global production capacity of HFCs and PFCs most often exceeds current demand. There are a number of HFC-134a plants in developed countries and one plant in a developing country with others planned; the few plants for other HFCs are almost exclusively in developed countries. The proposed European Community phase-out of HFC-134a in mobile air conditioners in new cars and the industry voluntary programme to reduce their HFC-134a emissions by 50% will affect demand and production capacity and output. Rapidly expanding markets in developing countries, in particular for replacements for CFCs, is resulting in new capacity for fluorinated gases which is at present being satisfied through the expansion of HCFC-22 and 141b capacity. [11]

IPCC/TEAP Special Report

Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons

Technical Summary

Coordinating Lead Authors

David de Jager (The Netherlands), Martin Manning (USA), Lambert Kuijpers (The Netherlands)

Lead Authors

Stephen O. Andersen (USA), Paul Ashford (UK), Paul Atkins (USA), Nick Campbell (France), Denis Clodic (France), Sukumar Devotta (India), Dave Godwin (USA), Jochen Harnisch (Germany), Malcolm Ko (USA), Suzanne Kocchi (USA), Sasha Madronich (USA), Bert Metz (The Netherlands), Leo Meyer (The Netherlands), José Roberto Moreira (Brazil), John Owens (USA), Roberto Peixoto (Brazil), José Pons (Venezuela), John Pyle (UK), Sally Rand (USA), Rajendra Shende (India), Theodore Shepherd (Canada), Stephan Sicars (Canada), Susan Solomon (USA), Guus Velders (The Netherlands), Dan Verdonik (USA), Robert Wickham (USA), Ashley Woodcock (UK), Paul Wright (UK) and Masaaki Yamabe (Japan)

Review Editors

Ogunlade Davidson (Sierra Leone), Mack McFarland (USA), Pauline Midgley (Germany)

1. Introduction

This IPCC Special Report was developed in response to invitations by the *United Nations Framework Convention on Climate Change* (UNFCCC)[1,2] and the *Montreal Protocol on Substances that Deplete the Ozone Layer*[3] to prepare a balanced scientific, technical and policy relevant report regarding alternatives to ozone-depleting substances (ODSs) that affect the global climate system. It has been prepared by the IPCC and the Technology and Economic Assessment Panel (TEAP) of the Montreal Protocol.

Because ODSs cause depletion of the stratospheric ozone layer[4], their production and consumption are controlled under the Montreal Protocol and consequently are being phased out, with efforts made by both developed and developing country parties to the Montreal Protocol. Both the ODSs and a number of their substitutes are greenhouse gases (GHGs) which contribute to climate change (see Figure TS-1). Some ODS substitutes, in particular hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), are covered under the UNFCCC and its Kyoto Protocol. Options

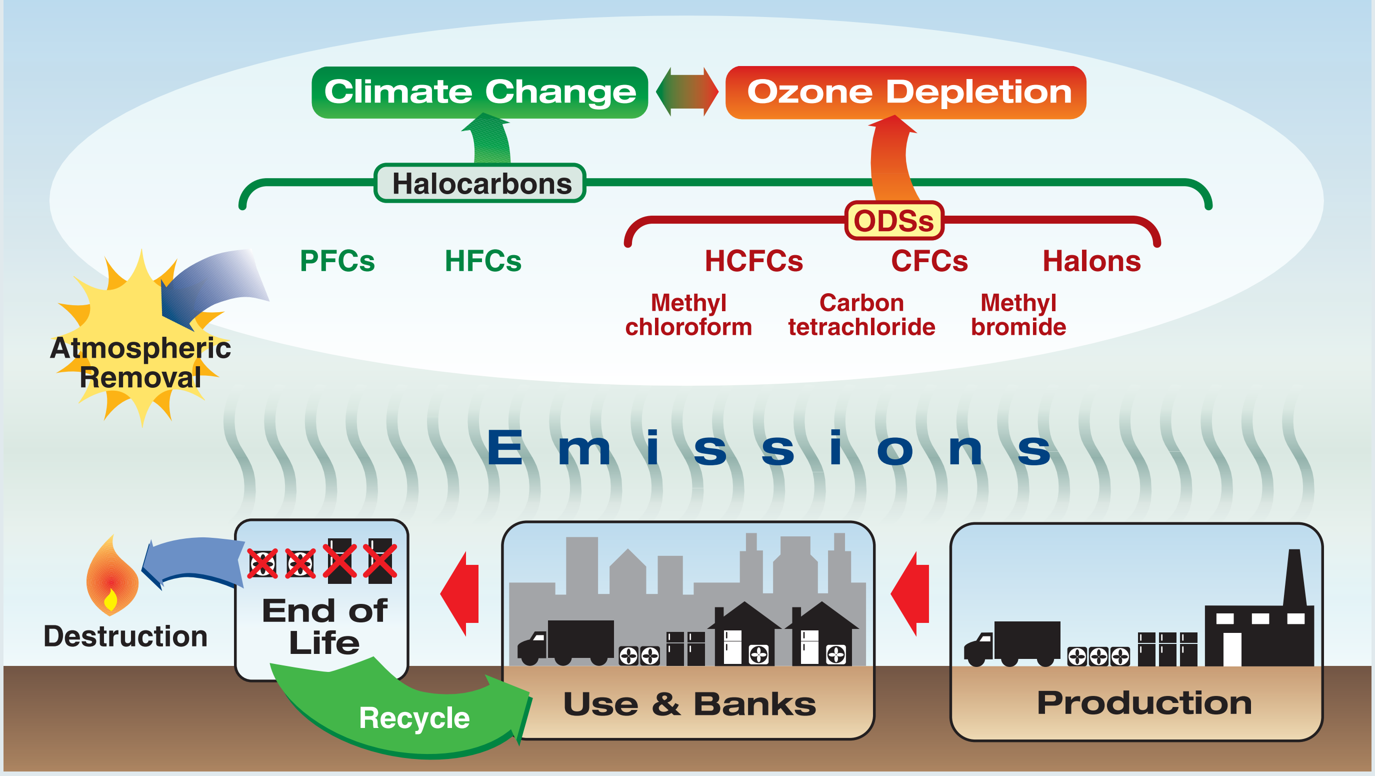


Figure TS-1. Schematic diagram of major issues addressed by this report. Chlorofluorocarbons (CFCs), halons and hydrochlorofluorocarbons (HCFCs) contribute to ozone depletion and climate change, while hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) contribute only to climate change and are among possible non-ozone depleting alternatives for ODSs. Red denotes gases included under the Montreal Protocol and its amendments and adjustments[5] while green denotes those included under the UNFCCC and its Kyoto Protocol. Options considered in this report for reducing halocarbon emissions include improved containment, recovery, recycling, destruction of byproducts and existing banks[6], and use of alternative processes, or substances with reduced or negligible global warming potentials.

---

[1] Decision 12/CP.8, FCCC/CP/2002/7/Add.1, page 30.
[2] Terms defined in the Glossary are highlighted in colour the first time they are used in this Technical Summary.
[3] Decision XIV/10 UNEP/OzL.Pro.14/9, page 42.
[4] Ozone within this report refers to stratospheric ozone unless otherwise noted.
[5] Hereafter referred to as the Montreal Protocol.
[6] Banks are the total amount of substances contained in existing equipment, chemical stockpiles, foams and other products not yet released to the atmosphere.

chosen to protect the ozone layer could influence climate change. Climate change may also indirectly influence the ozone layer.

This report considers the effects of total emissions of ODSs and their substitutes on the climate system and the ozone layer. In particular, this provides a context for understanding how replacement options could affect global warming. The report does not attempt to cover comprehensively the effect of replacement options on the ozone layer.

Hydrochlorofluorocarbons (HCFCs) have been used to replace chlorofluorocarbons (CFCs) in several applications as they have shorter lifetimes in the atmosphere and consequently cause less ozone depletion. HFCs and PFCs have been identified as potential long-term replacements for ODSs because they contain neither bromine nor chlorine and do not cause any significant ozone depletion. However, all of these species are also GHGs and so contribute to climate change in varying degrees. Additional alternatives for halocarbon use include ammonia and organic substances, the direct emissions of which have a very small effect on climate although indirect emissions may be important.

The report considers, by sector, options for reducing halocarbon emissions, options involving alternative substances, and technologies, to address greenhouse gas emissions reduction. It considers HFC and PFC emissions insofar as these relate to replacement of ODSs. HFC and PFC emissions from aluminum or semiconductor production or other sectors where ODS replacement is not involved are not covered.

The major application sectors using ODSs and their HFC/PFC substitutes include refrigeration, air conditioning, foams, aerosols, fire protection and solvents. Emissions of these substances originate from manufacture and any unintended byproduct releases, intentionally emissive applications, evaporation and leakage from banks contained in equipment and products during use, testing and maintenance, and end-of-life practices.

With regard to specific emission reduction options, the report generally limits its coverage to the period up to 2015, for which reliable literature is available on replacement options with significant market potential for these rapidly evolving sectors. Technical performance, potential assessment methodologies and indirect emissions[7] related to energy use are considered, as well as costs, human health and safety, implications for air quality, and future availability issues.

The Technical Summary (TS) brings together key information from the underlying report and follows to some extent the report structure, which is in three parts. The first part describes scientific links between stratospheric ozone depletion and climate change and provides relevant information on radiative forcing, observations of changes in forcing agents and emissions (section 2 of the TS). It addresses how the phase-out of ODSs is affecting both stratospheric ozone and climate change as well as the implications for air quality and local environmental issues. The report does not seek to cover the breadth and depth of other specialized assessments of ozone depletion and climate change, but rather to assess relevant interactions between the two environmental issues pertinent to the consideration of replacement options.

The second part assesses options to replace ODSs, including environmental, health, safety, availability and technical performance issues (section 3 and 4 of the TS). The report assesses practices and alternative technologies to reduce emissions and net warming impacts within each use sector, including consideration of process improvement in applications, improved containment, end-of-life recovery, recycling, disposal and destruction as well as relevant policies and measures.

The third part of the report covers supply and demand issues. The report aggregates available information on emissions from the various sectors and regions and considers the balance between supply and demand, bearing in mind those issues relevant to developing countries (section 3.8 in the TS).

---

[7] It should be noted that the National Inventory Reporting community uses the term 'indirect emissions' to refer specifically to those greenhouse gas emissions which arise from the breakdown of another substance in the environment. This is in contrast to the use of the term in this report, which specifically refers to energy-related CO_2 emissions associated with Life Cycle Assessment (LCA) approaches such as Total Equivalent Warming Impact (TEWI) or Life Cycle Climate Performance (LCCP).

2. Halocarbons, ozone depletion and climate change

2.1 How do the CFCs and their replacements contribute to the radiative forcing of the climate system?

Many halocarbons, including CFCs, PFCs, HFCs and HCFCs, are effective GHGs because they absorb Earth's outgoing infrared radiation in a spectral range where energy is not removed by CO_2 or water vapour (sometimes referred to as the *atmospheric window*, see Figure TS-2). Halocarbon molecules can be many thousand times more efficient at absorbing radiant energy emitted from the Earth than a molecule of CO_2 , and small amounts of these gases can contribute significantly to radiative forcing[8] of the climate system. [1.1][9]

Radiative efficiencies (W m^{-2} ppb^{-1}) for the halocarbons and other well-mixed GHGs that are reported under the Montreal and Kyoto Protocols are given in Table TS-1. For most of the species considered here, the magnitude of the direct radiative forcing generated by a gas is given by the product of its mixing ratio (in parts per billion, ppb) and radiative efficiency. For the more abundant greenhouse gases – CO_2, methane and nitrous oxide – there is a nonlinear relationship between mixing ratio and radiative forcing. [1.1]

The primary radiative effect of CO_2 and water vapour is to warm the surface climate but cool the stratosphere. However, due to their absorption in the atmospheric window, the direct radiative effect of halocarbons is to warm both the troposphere and stratosphere. [1.2 and Box 1.4]

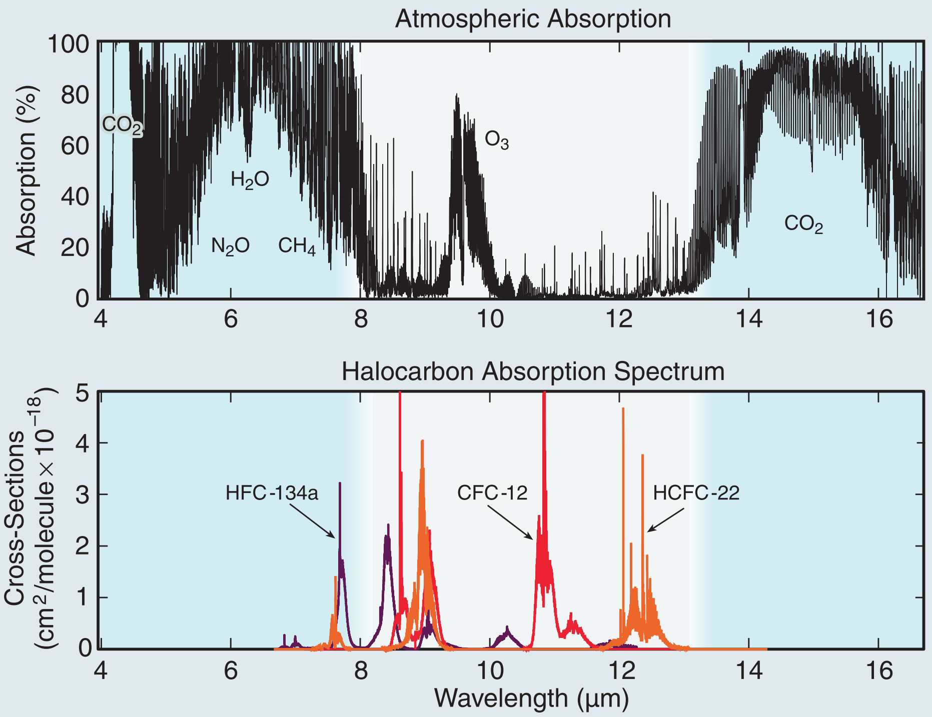


Figure TS-2. Top panel: Infrared atmospheric absorption (0 represents no absorption and 100% represents complete absorption of radiation) as derived from the space borne IMG/ADEOS radiance measurements (3 April 1997, 9.5°W, 38.4°N). Bottom panel: Absorption cross-sections for halocarbons (HCFC-22, CFC-12, HFC-134a) in the infrared atmospheric window, which lies between the nearly opaque regions due to strong absorptions by CO_2, H_2O, O_3, CH_4 and N_2O. [Figure 2.6]

---

[8] Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, and is an index of the importance of the factor as a potential climate change mechanism. It is expressed in watts per square meter (W m^{-2}). A greenhouse gas causes direct radiative forcing through absorption and emission of radiation and may cause indirect radiative forcing through chemical interactions that influence other greenhouse gases or particles.

[9] Numbers in square brackets indicate the sections in the main report where the underlying material and references for the paragraph can be found.

Table TS-1. Radiative efficiencies, lifetimes and positive direct radiative forcing for the well-mixed GHGs and halocarbons normally reported under the Montreal and Kyoto Protocols due to their increases between 1750 and 2000 and between 1970 and 2000. See Section 1.1, especially Table 1.1, and Section 2.2, especially Table 2.6, for details.

Gas species	Radiative efficiency ($W\ m^{-2}\ ppb^{-1}$)	Lifetime (years)	Radiative forcing ($W\ m^{-2}$)	
			1750–2000	1970–2000
CO_2	1.55×10^{-5} [a]	- [b]	1.50	0.67
CH_4	3.7×10^{-4}	12 [c]	0.49	0.13
N_2O	3.1×10^{-3}	114 [c]	0.15	0.068
CFC-11	0.25	45	0.066	0.053
CFC-12	0.32	100	0.173	0.136
CFC-113	0.3	85	0.025	0.023
CFC-114	0.31	300	0.005	0.003
CFC-115	0.18	1700	0.002	0.002
HCFC-22	0.20	12	0.0283	0.0263
HCFC-123	0.14	1.3	0.0000	0.0000
HCFC-124	0.22	5.8	0.0003	0.0003
HCFC-141b	0.14	9.3	0.0018	0.0018
HCFC-142b	0.2	17.9	0.0024	0.0024
HCFC-225ca	0.2	1.9	0.0000	0.0000
HCFC-225cb	0.32	5.8	0.0000	0.0000
HFC-23	0.19	270	0.0029	0.0029
HFC-32	0.11	4.9	0.0000	0.0000
HFC-125	0.23	29	0.0003	0.0003
HFC-134a	0.16	14	0.0024	0.0024
HFC-152a	0.09	1.4	0.0002	0.0002
HFC-227ea	0.26	34.2	0.0000	0.0000
Halon-1211	0.3	16	0.0012	0.0012
Halon-1301	0.32	65	0.0009	0.0009
Halon-2402	0.33	20	0.0001	0.0001
CCl_4	0.13	26	0.0127	0.0029
CH_3Br	0.01	0.7	0.0001	0.0000
CH_3CCl_3	0.06	5	0.0028	0.0018
CF_4	0.08	50,000	0.0029	0.0029
C_2F_6	0.26	10,000	0.0006	0.0006
C_3F_8	0.26	2600	0.0001	0.0001
Ethane	0.0032	0.21	-	-
Pentane	0.0046	0.010	-	-

Notes

[a] The radiative efficiency of CO_2 decreases as its concentration increases.

[b] Removal of CO_2 from the atmosphere involves many different processes and its rate cannot be expressed accurately with a single lifetime. However, carbon cycle models typically estimate that 30 to 50% of CO_2 emissions remain in the atmosphere for more than 100 years.

[c] The lifetimes of CH_4 and N_2O incorporate indirect effects of the emission of each gas on its own lifetime.

Apart from their direct effect on climate, some gases have an indirect effect either from radiative forcing caused by their degradation products or through their influences on atmospheric chemistry. Halocarbons containing chlorine and bromine are ODSs and, because ozone is a strong absorber of UV radiation, they have an indirect cooling effect which is significant compared to their direct warming effect. For hydrocarbons, indirect effects associated with tropospheric ozone production may be significantly greater than direct effects. [1.1, 1.5, Box 1.3, 2.2 and 2.5]

2.2 How long do CFCs and their replacements remain in the atmosphere after they are emitted?

Gases with longer lifetimes remain in the atmosphere, and consequently may affect climate, for a longer time. The lifetimes of several halocarbons and replacement species are given in Table TS-1. Most CFCs are removed from the atmosphere on time scales ranging from about 50 to 100 years. With the exception of HFC-23, which has a lifetime of 270 years, HCFCs and HFCs are removed efficiently in the troposphere through atmospheric chemistry oxidation processes. As a result, they have lifetimes ranging from about one year to a few decades. PFCs are very inert molecules and their emissions contribute to warming of the climate system over timescales that can exceed 1000 years. [2.2]

Most halocarbon gases are sufficiently long-lived that they become mixed throughout the atmosphere before they are destroyed. They therefore have nearly constant mixing ratios throughout the troposphere. In contrast, ammonia and organic compounds have lifetimes that typically range from days to weeks, thereby making their distributions variable both spatially and temporally. [2.2]

2.3 How are the atmospheric concentrations and emissions of CFCs, halons, HCFCs, HFCs and PFCs changing?

Atmospheric observations, as seen for example in Figure TS-3, show that global concentrations of the CFCs increased largely during the period from the 1970s to the 1990s, so that their contributions to radiative forcing grew mainly during this period, while the concentrations of replacement species are now increasing. HCFC-22 is the most abundant HCFC, with a current concentration of 160 ppt. Its concentration began to increase in the early 1970s concurrently with those of the CFCs, while the concentrations of other significant HCFCs increased mainly in the 1990s, as did those of the HFCs. [1.2, 2.3]

Currently observed rates of change differ among ODSs, depending mainly upon their emissions and atmospheric lifetimes (see Table TS-2). Following the Montreal Protocol and its subsequent amendments, large reductions in ODS production and emission have occurred. The concentrations of some CFCs have peaked, while others are expected to decline in the future. In the complete absence of emissions, the concentrations of these gases would decrease, but at a slow rate that is determined by their atmospheric lifetimes of decades to centuries. Continuing emissions will cause increases in the concentrations of these gases or diminish their rates of decrease. Observations of annual changes in atmospheric concentrations provide the most reliable estimates of total global emissions for long-lived gases. For example, CFC-11 is observed to be decreasing at a rate about 60% slower than would occur in the absence of emissions, while CFC-12 is still increasing slightly, indicating continuing emissions of both species. CFC-113, however, is decreasing at a rate close to that expected in the absence of emissions. Table TS-2 shows observed global concentrations and growth or decay rates of the major CFCs, halons, HCFCs, HFCs and PFCs, together with the estimated emissions to the atmosphere required to explain currently observed trends. [2.3, 2.5]

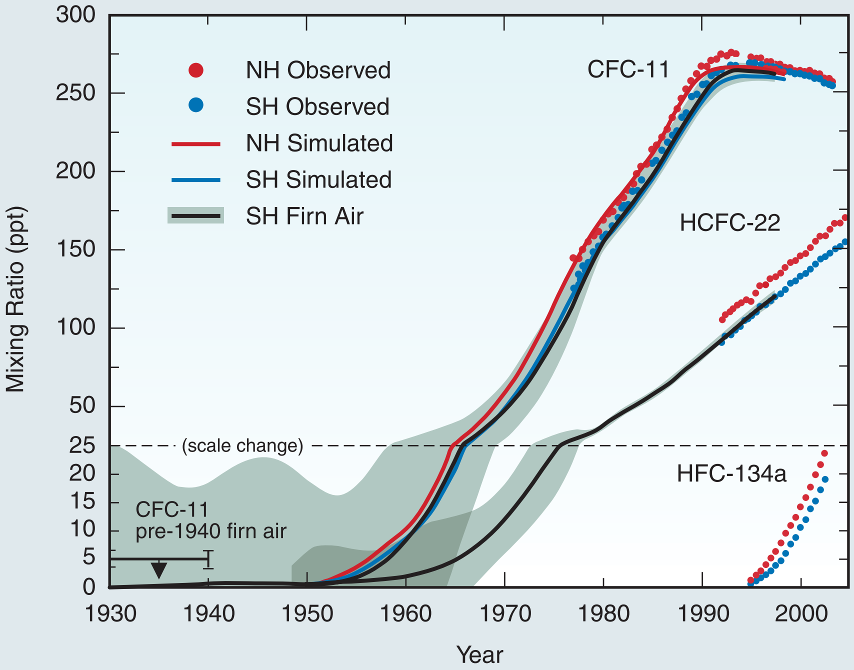


Figure TS-3. Estimated global tropospheric mixing ratios (ppt) for CFC-11, HCFC-22 and HFC-134a shown separately for the Northern and Southern Hemisphere. Red and blue symbols show measurements from the AGAGE (Advanced Global Atmospheric Gases Experiment) and CMDL (Climate Monitoring and Diagnostics Laboratory) networks, while red and blue lines show simulated CFC-11 concentrations based on estimates of emissions and atmospheric lifetimes. Black lines and the shaded area show estimates and uncertainty bands for CFC-11 and HCFC-22 derived by synthesis inversion of Antarctic firn air measurements and *in situ* Cape Grim atmospheric measurements. The thick black horizontal line with arrow and error bars shows a separate upper bound estimate of pre-1940 CFC-11 concentrations based on South Pole firn air measurements. Note that the gases shown here are used in different applications and are presented for illustrative purposes only. [Figure 1.8]

Table TS-2. Observed global concentrations and trends for some of the most abundant CFCs, HCFCs, HFCs and PFCs near the year 2003, together with the total global emissions required to explain these trends. For comparison estimated emissions are shown for the year 1990, a little after the peak in total ODS emissions. See Section 2.3, especially Table 2.1, and Figure 2.4 for details.

Species	Concentration in 2003[a] (ppt)	Trend between 2001 and 2003[a] (ppt yr^{-1})	Trend as percentage of concentration %	Estimated emission in 2002[b]		Estimated emissions in 1990[c]	
				(kt yr^{-1})	($GtCO_2$-eq yr^{-1})[d]	(kt yr^{-1})	($GtCO_2$-eq yr^{-1})[d]
CFC-11	256	-1.9 – -2.7	-0.7 – -1.1	70 – 90	0.33 – 0.42	280 – 300	1.31 – 1.40
CFC-12	538	+0.2 – +0.8	+0.04 – +0.16	110 – 130	1.2 – 1.4	400 – 430	4.29 – 4.61
CFC-113	80	-0.6 – -0.7	-0.8 – -1.0	5 – 12	0.03 – 0.07	180 –230	1.09 – 1.39
Total major CFCs				***185 – 232***	***1.54 – 1.89***	***860 – 960***	***6.68 – 7.40***
HCFC-22	157	+4.5 – +5.4	+2.8 – +3.4	240 – 260	0.43 – 0.46	185 – 205	0.33 – 0.36
HCFC-123	0.03	0	0	n.a.[e]		0	0
HCFC-141b	16	+1.0 – +1.2	+6.3 – +7.5	55 – 58	0.04	0	0
HCFC-142b	14	+0.7 – +0.8	+4.3 – +5.7	25	0.06	10 – 20	0.02 – 0.05
Total major HCFCs				***320 – 343***	***0.53 – 0.56***	***195 – 225***	***0.35 – 0.41***
HFC-23	17.5	+0.58	+3.3	13	0.19	6.4	0.09
HFC-125	2.7	+0.46	+17	9 – 10	0.03	0	0
HFC-134a	26	+3.8 – +4.1	+15 – +16	96 – 98	0.14	0	0
HFC-152a	2.6	+0.34	+13	21 – 22	0.003	0	0
Total major HFCs			***139 – 143***	***0.36***	***6.4***	***0.09***	
Halon-1211	4.3	+0.04 – +0.09	+0.9 – +2.8	7 – 8	0.013 – 0.015	11.5	0.02
Halon-1301	2.9	+0.04 – +0.08	+1.4 – +2.8	1 – 2	0.007 – 0.014	5.1	0.04
CCl_4	95	-0.9 – -1.0	-1.0 – -1.1	64 – 76	0.09 – 0.10	120 – 130	0.17 – 0.18
CH_3CCl_3	27	-5.6 – -5.8	-21 – -23	15 – 17	0.002	646	0.09
CF_4	76	n.a.[e]	n.a.[e]				
C_2F_6	2.9	+0.1	+3.4	n.a.[e]			
C_3F_8	0.26	n.a.[e]	n.a.[e]				

[a] Average of tropospheric concentrations and range of trends from different monitoring networks.

[b] Estimated from current concentrations and trends.

[c] Estimated emissions for 1990 based on Chapter 2, Figure 2.4, except for HFC-23 which is taken from Chapter 10.

[d] GWP-weighted emissions using direct GWPs from this report.

[e] n.a. – not available. Insufficient data to determine reliable trend or emission value.

For comparison, earlier estimates of emissions (WMO, 2003)[10] are also shown for the year 1990, which is slightly after the peak in ODS emissions. Emissions of CFC-113 and CH_3CCl_3, both used largely as solvents and having no accumulated banks, decreased by more than a factor of 10 from 1990 to 2000. Stratospheric chlorine levels have approximately stabilized and may have already started to decline. [2.3]

The estimated current emissions of CFC-11 and CFC-12 shown in Table TS-2 are larger than estimates of new production, indicating that a substantial fraction of these emissions originates from banks of these chemicals built up from past production. Such banks include material contained in foams, air conditioning, refrigeration and other applications. In contrast, production is currently greater than emission for nearly all of the HCFCs and HFCs, implying that banks of these chemicals are currently accumulating and could contribute to future radiative forcing. One measure of the relevance of such banks is the ratio of bank size to the amount already in the atmosphere. For example, in the case of HFC-134a these amounts are estimated to be about equal. [2.3, 2.5 and 11.3]

Continuing atmospheric observations of CFCs and other ODSs now enable improved validation of estimates for the lag between production and emission to the atmosphere. This provides new insight into the overall significance of banks and of end-of-life options which are relevant to the future use of HCFC and HFC substitutes. [2.5]

For some gases, there are now sufficient atmospheric observations to constrain not just global but also regional emissions in certain areas. For example, atmospheric measurements suggest sharp increases in European emissions of HFC-134a over the period 1995–1998 and in HFC-152a over the period 1996–2000, with some subsequent levelling off through to 2003. [2.3]

2.4 How much do the halocarbon gases and their replacements contribute to positive radiative forcing of the climate system relative to pre-industrial times? What about relative to 1970?

The contributions to direct radiative forcing due to increases in halocarbon concentrations from 1750 to 2000 and from 1970 to 2000 are summarized in Table TS-1 and Figure TS-4. The direct radiative forcing due to these increases from 1750 to 2000 is estimated to be 0.33 ± 0.03 W m^{-2}, which represents about 13% of the total due to increases in all of the well-mixed GHGs over that period. The contributions of CFCs, HCFCs and HFCs are about 0.27 W m^{-2}, 0.033 W m^{-2} and 0.006 W m^{-2} respectively. [1.1 and 1.5]

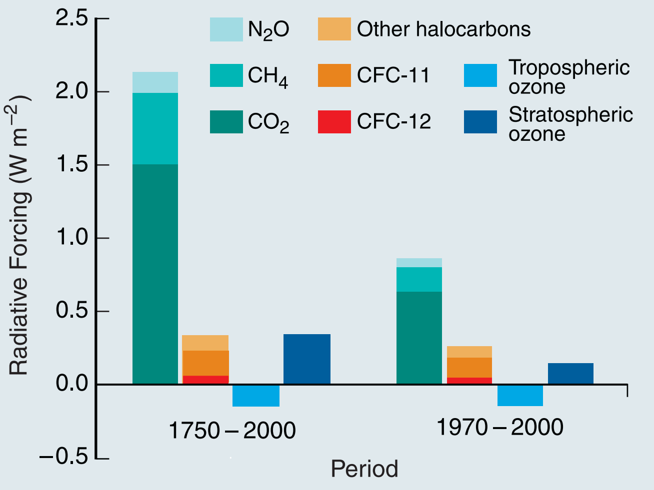


Figure TS-4. Radiative forcing (W m^{-2}) due to changes in well mixed GHGs and ozone over the time periods 1750 – 2000 and 1970 – 2000. The negative radiative forcing from stratospheric ozone is due to stratospheric ozone depletion resulting from halocarbon emissions between 1970 and 2000. In contrast, the tropospheric ozone radiative forcing is largely independent of the halocarbon radiative forcing. [Figure 1.3]

Because increases in halocarbon concentrations occurred mainly during the last three decades, their relative contribution to total radiative forcing is larger during this period. The direct radiative forcing due to increases in halocarbons from 1970 to 2000 was 0.27 ± 0.03 W m^{-2}, which represents about 23% of that due to increases in all of the well-mixed GHGs. The contribution to direct radiative forcing due to HCFCs is presently dominated by HCFC-22, while that due to HFCs is dominated by HFC-134a and HFC-23, with the latter being emitted mainly as a byproduct of manufacture of HCFC-22. [1.1, 1.5]

---

[10] WMO, 2003: Scientific Assessment of Ozone Depletion: 2002. Global Ozone Research and Monitoring Project – Report No. 47, World Meteorological Organization, Geneva, 498 pp.

2.5 How has stratospheric ozone changed in recent decades and why?

As shown in Figure TS-5, the amount of stratospheric ozone has decreased over the past few decades, particularly in the Antarctic. The largest decreases since 1980 have been observed over the Antarctic during the spring (the *Antarctic ozone hole*), with the monthly total column ozone amounts in September and October being about 40–50% below pre-ozone-hole values. [1.2, 1.3 and 1.4]

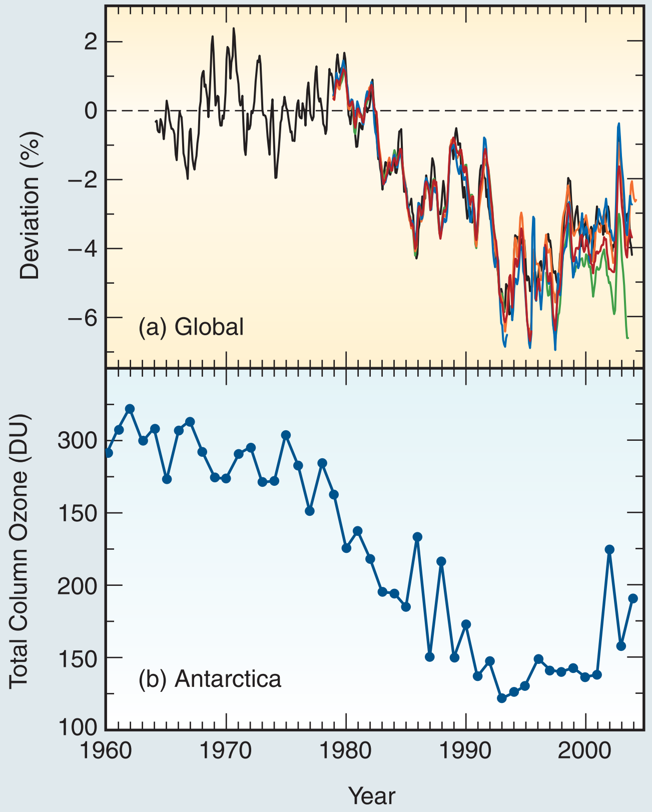


Figure TS-5. Top: Time-series of de-seasonalized global mean column ozone anomalies estimated from five different data sets, based on ground-based (black line) and satellite measurements (colored lines). Anomalies are expressed as percentages of the time average for the period 1964–1980. Bottom: October mean total column ozone measurements from the Dobson spectrophotometer at Halley, Antarctica (73.5°S, 26.7°W). [Figures 1.4 and 1.5]

Arctic ozone loss in any given year depends strongly on the meteorological conditions. Arctic ozone has been chemically depleted by up to 30% in recent cold years, but the losses observed in warm years have been very small. Globally averaged ozone has decreased by roughly 3% since 1980. The ozone column decreased by about 6% over the mid-latitudes (35°–60°) in the Southern Hemisphere and 3% in the Northern Hemisphere. Significant long-term changes in column ozone have not been observed in the tropics. Observations and model calculations suggest that the global average amount of ozone depletion has now approximately stabilized (see Figure TS-5). [1.2]

The observed ozone changes are caused by both chemical and dynamical factors, with the chemical factors being dominant. This ozone depletion is caused primarily by increases in concentrations of reactive chlorine and bromine compounds that are produced by degradation of anthropogenic ODSs, including halons, CFCs, HCFCs, methyl chloroform (CH_3CCl_3), carbon tetrachloride (CCl_4) and methyl bromide (CH_3Br). Human activities have increased the amount of chlorine in the stratosphere, relative to estimated natural background levels, by a factor of about 5 since 1970. CFCs are the primary source of this change, while HCFCs currently contribute about 5% to the total stratospheric chlorine loading. [1.2, 1.3 and 1.4]

2.6 How has ozone depletion affected the radiative forcing of the climate system?

Observations and modelling show that ozone depletion has acted to cool the stratosphere, which in turn can contribute to cooling of the troposphere and surface. The warming of the climate by ODSs and the cooling associated with ozone depletion are two distinct mechanisms that are governed by different physical processes and feedbacks and for which there are quite different levels of scientific understanding. For the purposes of this report, we follow IPCC (2001)[11] and assume that the observed depletion is caused entirely by ODSs and that the ozone radiative forcing can be considered to be an indirect effect due to ODSs. Gases containing bromine (such as halons) are particularly effective ozone depleters and have a larger contribution to the indirect effect on a per-molecule basis than other ozone-depleting gases such as the CFCs. [1.1, 1.2, 1.3 and 1.5]

---

[11] IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 944 pp.

The best estimate of the negative indirect radiative forcing associated with ozone depletion over the period 1970–2000 is –0.15 ± 0.10 W m^{-2}, where the large uncertainty is determined by the range of model estimates and arises mainly because of uncertainties in the detailed vertical distribution of ozone depletion. This indirect effect is *very likely*[12] to be smaller in magnitude than the positive direct radiative forcing due to ODSs alone (0.32 ± 0.03 W m^{-2}) which is far better understood . If some fraction of the observed global ozone changes were not attributable to ODSs the magnitude of this indirect effect would be reduced. [1.5]

The relative contributions of different types of gas to positive direct and negative indirect radiative forcing are shown in Figure TS-6. However, the warming and cooling effects produced by direct and indirect radiative forcing do not simply offset one another because the spatial and seasonal distributions of the effects on surface climate are different. [1.2, 1.5 and Box 1.4]

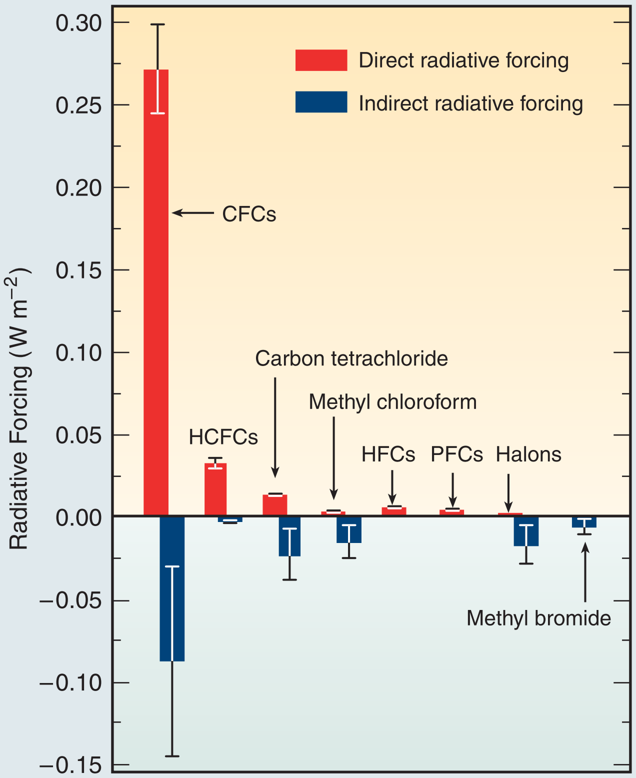


Figure TS-6. Radiative forcing due to changes in halocarbons from 1750 to 2000. [Based on Table 1.1]

A limited number of global climate modelling and statistical studies suggest that ozone depletion is one mechanism that may affect patterns of climate variability which are important for tropospheric circulation and temperatures in both hemispheres. In particular, the significant depletion of stratospheric ozone occurring in the Antarctic region is *likely* to have affected stratospheric circulation, and consequently the troposphere. There are indications that the Antarctic ozone hole has contributed to the cooling observed over the Antarctic plateau and to warming in the region of the Antarctic Peninsula. [1.3]

2.7 What factors are expected to control ozone in the coming century? Will it 'recover' to pre-ozone-hole values? Has the recovery already begun?

Global ozone recovery is expected to follow decreases in chlorine and bromine loading in the stratosphere as ODS concentrations decline due to reductions in their emissions. While this is expected to be the dominant factor in ozone recovery, emissions of other GHGs (such as CO_2, methane and nitrous oxide) can affect both tropospheric and stratospheric chemistry and climate, and will have some effect on ozone recovery. [1.3 and 1.4]

Figure TS-7 shows a range of predictions for changes in stratospheric ozone for the latitude range 60°S–60°N from two-dimensional photochemical models together with comparable ground-based and satellite measurements taken up to 2003. Such computer simulations show global ozone recovery occurring gradually as halogen gas emissions and concentrations decrease. However, the time of recovery varies significantly, depending on assumptions made about future climate and future composition of the atmosphere, and consequently remains quite uncertain. [1.4 and Box 1.7]

Future temperature changes related to GHG emissions are expected to enhance stratospheric ozone depletion in some parts of the stratosphere and decrease it in others. Increases in CO_2 concentration are expected to cool the stratosphere, which is known to reduce the rates of gas-phase ozone destruction in much of the stratosphere and thereby increase ozone concentrations at altitudes above about 25 km. In contrast, lower temperatures could decrease ozone concentrations at lower altitudes. While the latter effect is expected to be most important in the Arctic in late winter to early spring, it may be small compared with other

---

[12] In this report the following words have been used where appropriate to indicate judgmental estimates of confidence: *very likely* (90–99% chance); *likely* (66–90% chance); *unlikely* (10–33% chance); and *very unlikely* (1–10% chance).

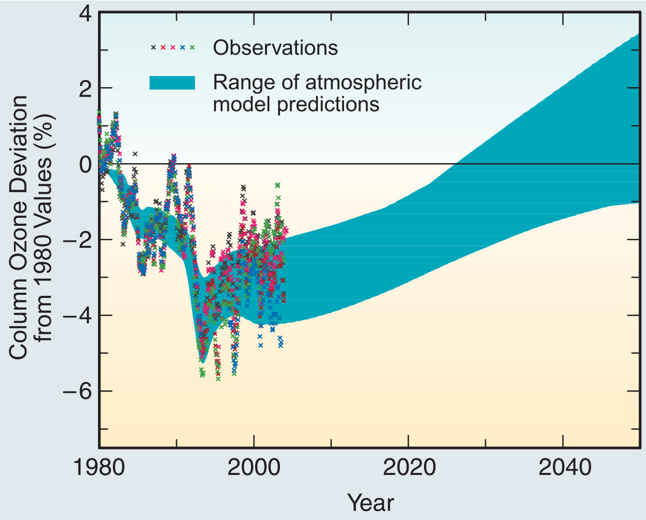


Figure TS-7. Observed and modelled changes in low- and mid-latitude (60°S – 60°N) de-seasonalised column ozone relative to 1980. The black symbols indicate ground-based measurements, and the coloured symbols various satellite-based data sets. The range of model predictions comes from the use of several different two-dimensional photochemistry models forced with the same halocarbon scenario; some models also allowed for the effect of changing CO_2 amounts on stratospheric temperatures. The measurements show that column ozone values between 60°S and 60°N decreased beginning in the early 1980s and the models capture the timing and extent of this decrease quite well. Modelled halogen source gas concentrations decrease in the early 21st century in response to the Montreal Protocol, so that simulated ozone values increase and recover towards pre-1980 values. [Box 1.7]

processes and will slowly decrease with time as the chlorine and bromine loadings decrease. Changes in stratospheric circulation may also occur in association with increases in GHGs and these could either increase or decrease future mid-latitude and polar ozone. The net result of future GHG emissions on global ozone depends upon the combination of these effects and its magnitude and direction are poorly quantified at present. [1.3 and 1.4]

As can be seen from the measurements shown in Figure TS-7, detection of the beginning of ozone recovery is difficult because of the high variability in ozone levels. This variability is due to both meteorological variability and the confounding influence of volcanic eruptions on the ozone layer. As a result, it is not yet possible to state that the beginning of ozone recovery has been unambiguously identified. [1.2, 1.4 and Box 1.7]

Models suggest that minimum levels of Antarctic ozone may already have occurred or should occur within the next few years. Predictions of the timing of a minimum in Arctic ozone are more uncertain due to far greater natural variability in this region, but models suggest that it should occur within the next two decades. An Arctic 'ozone hole' similar to that currently observed over the Antarctic is *very unlikely* to occur. [1.3 and 1.4]

2.8 How much are CFCs, HCFCs and their possible replacements expected to affect the future radiative forcing of the climate system?

The estimated radiative forcing of HFCs in 2015 is in the range 0.022–0.025 W m^{-2} based on the SRES emission scenarios and in the range 0.019–0.030 W m^{-2} based on scenarios from Chapter 11 of this report. The radiative forcing of PFCs in 2015 is about 0.006 W m^{-2} based on SRES scenarios. These HFC and PFC radiative forcings correspond to about 6–10% and 2% respectively of the total estimated radiative forcing due to CFCs and HCFCs in 2015 (estimated to be 0.297 W m^{-2} for the baseline scenario). [2.5 and 11.5]

Scenario-based projections of future radiative forcing are shown in Figure TS-8. Such projections over longer time scales become more uncertain due to the growing influences of uncertainties in future technological practices and policies, but the contribution of HFCs may be 0.1 to 0.25 W m^{-2} by 2100 based upon the range of SRES emission scenarios, while that of PFCs may be 0.02 to 0.04 W m^{-2} by 2100. [1.5 and 2.5]

Figure TS-8 shows estimates of the separate contributions to future halocarbon radiative forcing from: past emissions (i.e. what is currently in the atmosphere); future emissions of new production assuming no change in current practices (based on the WMO Ab scenario); and emissions from current banks of halocarbons. Two different estimates of this last component are shown, one based on the WMO (2003) Ozone Assessment and the other based on later sections of this report. Although the magnitude of current ODS banks remains uncertain, their contribution to radiative forcing is expected to be comparable with that of HFC emissions to the atmosphere in the next few decades. This indicates that choices with respect to end-of-life options, such as the destruction of currently banked material, can provide significant benefits for the climate system. End-of-life recovery, recycling and destruction practices could also reduce emissions of all newly produced halocarbons and their contribution to radiative forcing shown in Figure TS-8. [1.5]

In addition to reducing atmospheric chlorine loading, actions taken under the Montreal Protocol and its adjustments and amendments have also acted to reduce total CO_2-equivalent

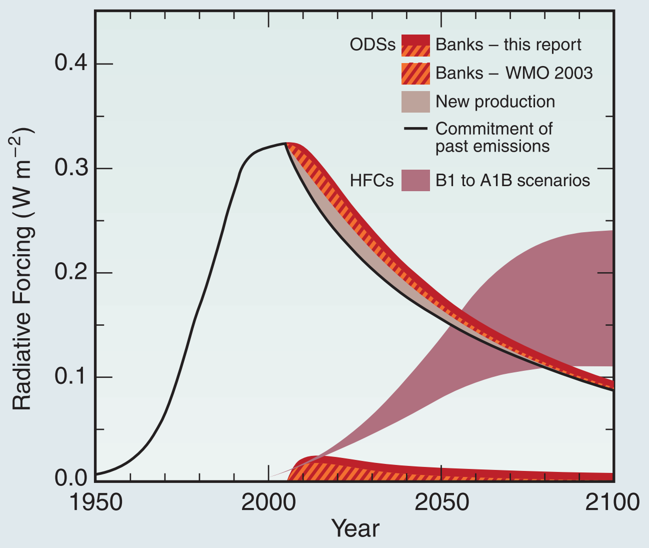


Figure TS-8. Direct radiative forcing of all ODSs compared with that of SRES projections for HFCs. The direct radiative forcing is split up into contributions from the commitment of past emissions (solid black line), release of allowed new production under the Montreal Protocol (grey shaded area), and release from ODS banks existing in 2004. Two estimates are given for these latter emissions – see Chapter 2. Radiative forcing due to HFCs are shown for the SRES B1 and A1B scenarios (boundaries of the purple shaded area). The contribution due to the delayed release of ODSs in banks is shown separately and is comparable with that projected due to HFCs for the next two decades. ODSs also have other indirect effects on radiative forcing. [Figure 1.19]

emissions. This has occurred because the replacement species generally have lower global warming potentials (GWPs) and because total halocarbon emissions have been reduced. The reduction can be seen by comparing emissions in 1990 and in 2000 given in Table TS-2, and is shown more generally in Figure TS-9. Thus the combined CO_2-equivalent emissions of CFCs, HCFCs and HFCs have decreased from a peak of 7.5 ± 0.4 $GtCO_2$-eq yr^{-1} around 1990 to 2.5 ± 0.2 $GtCO_2$-eq yr^{-1} around 2000, which is equivalent to about 10% of the annual contribution due to global fossil fuel burning in that year. [2.3 and 2.5]

Ammonia and those hydrocarbons used as halocarbon substitutes have atmospheric lifetimes ranging from days to months, and the direct and indirect radiative forcings associated with their use as substitutes are *very likely* to have a negligible effect on global climate.

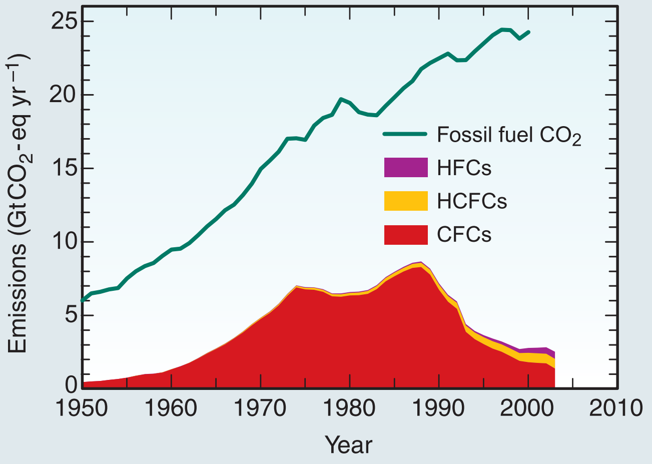


Figure TS-9. Direct GWP-weighted emissions (100-yr time horizon) for CFCs and HCFCs and HFCs compared with total CO_2 emissions due to fossil fuel combustion and cement production. [Figure 2.11]

2.9 What is the global warming potential and how is it used?

The GWP is a measure of the future radiative effect of an emission of a substance relative to the emission of the same amount of CO_2 integrated over a chosen time horizon. The GWP value for a species is proportional to its radiative efficiency and increases with its lifetime in the atmosphere. GWPs are most useful as relative measures of the climate response due to direct radiative forcing of well-mixed greenhouse gases whose atmospheric lifetimes are controlled by similar processes, which includes most of the halocarbons. [2.5 and Box 2.4]

The choice of time horizon is a policy consideration and makes a compromise between the relative weighting of short-term and long-term effects. Current practice most often uses GWPs calculated with a 100-year time horizon. This does not take into account the full effect of very long-lived gases with high radiative efficiency, such as PFCs, that persist in the atmosphere for much longer than 100 years. Similarly, integrating over 100 years reduces the contribution of short-lived species that last for only part of that period, relative to that of CO_2 which continues to contribute to radiative forcing throughout the 100-year time horizon and beyond. [2.5]

Table TS-3. GWPs of halocarbons commonly reported under the Montreal Protocol and the UNFCCC and its Kyoto Protocol and assessed in this report relative to CO_2, for a 100-year time horizon, together with their lifetimes and GWPs used for reporting under the UNFCCC. Gases shown in blue (darker shading) are covered under the Montreal Protocol and gases shown in yellow (lighter shading) are covered under the UNFCCC. [Tables 2.6 and 2.7]

Gas	GWP for direct radiative forcing[a]	GWP for indirect radiative forcing (Emission in 2005[b])	Lifetime (years)	UNFCCC Reporting GWP[c]
CFCs				
CFC-12	10,720 ± 3750	–1920 ± 1630	100	n.a.[d]
CFC-114	9880 ± 3460	Not available	300	n.a.[d]
CFC-115	7250 ± 2540	Not available	1700	n.a.[d]
CFC-113	6030 ± 2110	–2250 ± 1890	85	n.a.[d]
CFC-11	4680 ± 1640	–3420 ± 2710	45	n.a.[d]
HCFCs				
HCFC-142b	2270 ± 800	–337 ± 237	17.9	n.a.[d]
HCFC-22	1780 ± 620	–269 ± 183	12	n.a.[d]
HCFC-141b	713 ± 250	–631 ± 424	9.3	n.a.[d]
HCFC-124	599 ± 210	–114 ± 76	5.8	n.a.[d]
HCFC-225cb	586 ± 205	–148 ± 98	5.8	n.a.[d]
HCFC-225ca	120 ± 42	–91 ± 60	1.9	n.a.[d]
HCFC-123	76 ± 27	–82 ± 55	1.3	n.a.[d]
HFCs				
HFC-23	14,310 ± 5000	~0	270	11,700
HFC-143a	4400 ± 1540	~0	52	3800
HFC-125	3450 ± 1210	~0	29	2800
HFC-227ea	3140 ± 1100	~0	34.2	2900
HFC-43-10mee	1610 ± 560	~0	15.9	1300
HFC-134a	1410 ± 490	~0	14	1300
HFC-245fa	1020 ± 360	~0	7.6	–[e]
HFC-365mfc	782 ± 270	~0	8.6	–[e]
HFC-32	670 ± 240	~0	4.9	650
HFC-152a	122 ± 43	~0	1.4	140
PFCs				
C_2F_6	12,010 ± 4200	~0	10,000	9200
C_6F_{14}	9140 ± 3200	~0	3200	7400
CF_4	5820 ± 2040	~0	50,000	6500
Halons				
Halon-1301	7030 ± 2460	–32,900 ± 27,100	65	n.a.[d]
Halon-1211	1860 ± 650	–28,200 ± 19,600	16	n.a.[d]
Halon-2402	1620 ± 570	–43,100 ± 30,800	20	n.a.[d]
Other Halocarbons				
Carbon tetrachloride (CCl_4)	1380 ± 480	–3330 ± 2460	26	n.a.[d]
Methyl chloroform (CH_3CCl_3)	144 ± 50	–610 ± 407	5.0	n.a.[d]
Methyl bromide (CH_3Br)	5 ± 2	–1610 ± 1070	0.7	n.a.[d]

[a] Uncertainties in GWPs for direct positive radiative forcing are taken to be ±35% (2 standard deviations) (IPCC, 2001).

[b] Uncertainties in GWPs for indirect negative radiative forcing consider estimated uncertainty in the time of recovery of the ozone layer as well as uncertainty in the negative radiative forcing due to ozone depletion.

[c] The UNFCCC reporting guidelines use GWP values from the IPCC Second Assessment Report (see FCCC/SBSTA/2004/8, http://unfccc.int/resource/docs/2004/sbsta/08.pdf).

[d] ODSs are not covered under the UNFCCC.

[e] The IPCC Second Assessment Report does not contain GWP values for HFC-245fa and HFC-365mfc. However, the UNFCCC reporting guidelines contain provisions relating to the reporting of emissions from all greenhouse gases for which IPCC-assessed GWP values exist.

Direct GWP values are given in Table TS-3. These were changed in the IPCC Third Assessment Report (IPCC, 2001) relative to the previous assessment (IPCC, 1996)[13] due to revisions to the radiative efficiency of CO_2 and to some lifetimes and radiative efficiencies for other species. Revisions to GWP values given for some species in this report are due mainly to the use of updated lifetimes as described in section 2.5.4. [2.5]

The indirect GWPs associated with ozone depletion caused by the different ODSs are given in Table TS-3. As ODS indirect cooling effects are projected to cease upon ozone layer recovery, their duration depends not only on gas lifetime but also on the time of ozone recovery. Estimates of indirect GWPs incorporate this latter dependence by setting all indirect effects to zero after the time at which equivalent effective stratospheric chlorine (EESC) is estimated to return to its pre-1980 values. Indirect GWPs therefore depend on the year of emission and have large uncertainties arising from: uncertainty in the radiative forcing caused by ozone depletion; uncertainties in the amount of EESC attributed to each species; and uncertainty in the time at which EESC returns to its pre-1980 values. [1.5 and 2.5]

Given the very different levels of scientific understanding and relative uncertainties associated with direct and indirect radiative forcing of ODSs, the lack of cancellation in their effects on surface climate and the dependence of indirect GWPs on the year of emission, this report does not consider the use of net GWPs combining direct and indirect effects. Where direct GWPs are used with ODS emissions, or to construct CO_2-equivalent values, it should be recognized that there are also indirect effects that may be significant over the next several decades. [1.2, 1.5, Box 1.4 and 2.5]

2.10 Are HCFCs, HFCs or their replacements expected to have other effects on future environmental chemistry?

The emissions of organic gases (including HCFCs, HFCs, PFCs and hydrocarbons) and ammonia due to the replacement of ODSs in refrigeration and air conditioning are not expected to have significant large-scale impacts on air quality. The local impact of hydrocarbon and ammonia substitutes can be estimated by comparing the anticipated emission to local emissions from all sources. Small but not negligible impacts could occur near localized emission sources and such increases may be of concern, for instance, in areas that currently fail to meet local standards. [2.4 and 2.6]

Persistent degradation products of HFCs and HCFCs (such as trifluoroacetic acid, TFA) are removed from the atmosphere via deposition and washout processes and TFA is toxic to some aquatic life at concentrations approaching 1 mg L^{-1}. However, degradation of identified sources cannot account for the observed TFA abundances in the oceans, surface waters and atmosphere, indicating that there are larger natural sources of TFA. Current observations show typical concentrations in the ocean of about 0.2 $\mu g\ L^{-1}$, while concentrations as high as 40 $\mu g\ L^{-1}$ have been observed in the Dead Sea and Nevada lakes, suggesting a linkage to salt chemistry. Calculations based on projected HCFC and HFC emissions suggest that the concentration of TFA in rain-water due to their degradation is expected to be between 0.1 $\mu g\ L^{-1}$ and 0.5 $\mu g\ L^{-1}$ in the year 2010. Thus increases to toxic levels of 1 mg L^{-1} in specific ecosystems resulting from use of halocarbons are not supported by current studies. [2.4]

---

[13] IPCC, 1996: Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T., L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 572 pp.

3. Options for ODS phase-out and reducing GHG emissions

3.1 Where do GHG emissions occur that are related to the use of ODSs and their substitutes?

Ozone-depleting substances (ODSs) and their substitutes are being used in a wide range of products and processes. Many of these substances (or byproducts released during manufacture) are greenhouse gases (GHGs), the emissions of which will result in a contribution to the direct positive forcing of the climate. Direct emissions of GHGs may occur during the manufacture of these substances, during their use in products and processes and at the end of the life of these products (see Figure TS-1). Banks are the total amount of substances contained in existing equipment, chemical stockpiles, foams and other products, which are not yet released to the atmosphere.

The indirect GHG emissions of applications of ODSs and their replacements are the GHG emissions related to the energy consumption (fuels and electricity) during the entire life cycle of the application[7]. This effect is different from the indirect negative radiative forcing of ODSs discussed in preceding sections.

The UNFCCC addresses anthropogenic emissions by sources and the removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, and its Kyoto protocol regulates emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), HFCs, PFCs and sulphur hexafluoride (SF_6). The Montreal Protocol, on the other hand, controls not the emission but rather the production and consumption of ODSs. Thus, the emissions due to releases of CFCs and HCFCs present in banks (e.g. refrigeration equipment, foams) are not covered by either the Montreal Protocol or Climate Convention and Kyoto Protocol. These emissions could make a significant future contribution to global warming.

3.2 How are estimated banks and emissions projected to develop during the period 2002 to 2015?

Current banks and emissions

Current emission profiles of ODSs and their substitutes are largely determined by historical use patterns, resulting in a relatively high contribution (at the present time and in the coming decades) from the CFCs and HCFCs banked in equipment and foams. Annual emissions of CFCs, HCFCs, HFCs and PFCs[14] in 2002 were about 2.5 $GtCO_2$-eq yr^{-1} (see Table TS-4[15,16]). Refrigeration applications together with stationary air conditioning (SAC) and mobile air conditioning (MAC) contribute the bulk of global direct GHG emissions. About 80% of the 2002 emissions are CFCs and HCFCs.

The banks stored in equipment and foams may leak during the use phase of the products they are part of and at the end of the product life cycle (if they are not recovered or destructed). The bank-turnover varies significantly from application to application: from months (e.g. solvents) to several years (refrigeration applications) to over half a century (foam insulation).

Banks of CFCs, HCFCs, HFCs and PFCs were estimated at about 21 $GtCO_2$-eq (2002). CFCs, HCFCs and HFCs contribute about 16, 4 and 1 $GtCO_2$-eq, respectively (see Table TS-5), while banks of PFCs used as ODS replacements contribute only about 0.005 GtCO2-eq. The build-up of the banks of (relatively) new applications of HFCs will significantly determine future (>2015) emissions without additional bank management measures.

---

[14] This concerns only emissions of HFCs and PFCs that result from their use as ODS-substitutes. Total emissions of HFCs and notably PFCs are higher because of emissions from other applications that are not within the scope of this report (e.g. emissions from aluminum production and the semiconductor industry).

[15] Greenhouse gas (GHG) emissions and banks expressed in terms of CO_2-equivalents use GWPs for direct radiative forcing for a 100-year time horizon. Unless stated otherwise, the most recent scientific values for the GWPs are used, as assessed in this report and as presented in Table TS-3.

[16] Halons cause much larger negative indirect radiative forcing than positive direct radiative forcing and, in the interest of clarity, their effects are not included in estimates of total emissions and banks expressed in $MtCO_2$-equivalents.

Table TS-4. Greenhouse gas CO_2-equivalent (GWP-weighted) annual emissions of halons, CFCs, HCFCs and HFCs and of PFCs that are used as ODS substitutes: Breakdown per group of GHGs and per emission sector. Historical data for 2002, and business-as-usual (BAU) projections for 2015 emissions and emissions under a mitigation scenario (MIT) in 2015. The reduction potential is the difference between 2015 BAU and mitigation projections.
Note: Direct GWPs for a 100-year time horizon were used from IPCC (2001) and WMO (2003) (as listed in Table TS-3) 'Total' may not add up, due to rounding.

2002	**Annual emissions ($MtCO_2$-eq yr^{-1})**								
	Refrigeration[a]	SAC[b]	MAC[c]	Foams	Medical aerosols	Fire protection	HFC-23 byproduct	Other[d]	Total
Halons[e]	-	-	-	-	-	[47][e]	-	-	[47][e]
CFCs	726	99	641	117	69	0	-	0	1651
HCFCs	232	164	15	32	-	0.1	-	6	447
HFCs	102	9	93	3	6	1	195	25	434
PFCs	0	0	0	0	-	0.1	-	1	1
Total[e]	**1060**	**271**	**749**	**152**	**75**	**1**	**195**	**32**	**2534**

2015 BAU scenario	**Annual emissions ($MtCO_2$-eq yr^{-1})**								
	Refrigeration	SAC	MAC	Foams	Medical aerosols	Fire protection	HFC-23 byproduct	Other	Total
Halons	-	-	-	-	-	[12][e]	-	-	[12][e]
CFCs	136	50	49	85	17	0	-	0	338
HCFCs	570	210	19	20	-	0.1	-	9	828
HFCs	391	109	247	18	23	4	332	27	1153
PFCs	0	0	0	0	-	0.1	-	0.1	0.2
Total[e]	**1097**	**370**	**315**	**124**	**40**	**5**	**332**	**37**	**2319**

2015 Mitigation scenario	**Annual emissions ($MtCO_2$-eq yr^{-1})**								
	Refrigeration	SAC	MAC	Foams	Medical aerosols	Fire protection	HFC-23 byproduct	Other	Total
Halons	-	-	-	-	-	[12][e]	-	-	[12][e]
CFCs	84	24	32	81	0	0	-	0	221
HCFCs	359	86	12	17	-	0.1	-	9	484
HFCs	164	60	92	9	26	4	33	27	416
PFCs	0	0	0	0	-	0.1	-	0.1	0.2
Total[e]	**607**	**170**	**136**	**107**	**26**	**5**	**33**	**37**	**1121**

2015 Reduction potential	**Emissions reduction ($MtCO_2$-eq yr^{-1})**								
	Refrigeration	SAC	MAC	Foams	Medical aerosols	Fire protection	HFC-23 byproduct	Other	Total
Halons	-	-	-	-	-	n.q.	-	-	-
CFCs	53	26	17	4	17	-	-	-	117
HCFCs	210	124	7	3	-	n.q.	-	n.q.	344
HFCs	227	49	155	10	-3	n.q.	299	n.q.	737
PFCs	-	-	-	-	-	-	-	-	0
Total[e]	**490**	**200**	**179**	**17**	**14**	**n.q.**	**299**	**n.q.**	**1198**

Notes:
n.q. Not quantified

[a] 'Refrigeration' comprises domestic, commercial, industrial (including food processing and cold storage) and transportation refrigeration.

[b] 'SAC' (stationary air conditioning) comprises residential and commercial air conditioning and heating.

[c] 'MAC'(mobile air conditioning) applies to cars, buses and passenger compartments of trucks.

[d] 'Other' includes non-medical aerosols and solvents

[e] Halons cause much larger negative indirect than positive direct radiative forcing and, in the interest of clarity, their effects are not included in the totals and are shown in brackets in the table.

Table TS-5. Greenhouse gas CO$_2$-equivalent (GWP-weighted) banks of halons, CFCs, HCFCs and HFCs and of PFCs that are used as ODS substitutes: Breakdown per group of GHGs and per emission sector. Historical data for 2002 and BAU and MIT projections for 2015
Note: Direct GWPs for a 100-year time horizon were used from IPCC (2001) and WMO (2003) (as listed in Table TS-3). 'Total' may not add up, due to rounding.

2002	**Banks (MtCO$_2$-eq yr^{-1})**							
	Refrigeration[a]	SAC[b]	MAC[c]	Foams	Medical aerosols[f]	Fire protection	Other[d,f]	Total
Halons[e]	-	-	-	-	-	[531][e]	-	[531][e]
CFCs	3423	631	1600	10,026	69	0	0	15,749
HCFCs	810	1755	36	1229	-	5	6	3841
HFCs	518	123	350	16	6	65	25	1103
PFCs	0	0	0	0	-	4	1	5
Total[e]	**4751**	**2509**	**1987**	**11,270**	**75**	**74**	**32**	**20,698**

2015 BAU scenario	**Banks (MtCO$_2$-eq yr^{-1})**							
	Refrigeration[a]	SAC[b]	MAC[c]	Foams	Medical aerosols[f]	Fire protection	Other[d,f]	Total
Halons	-	-	-	-	-	[206][e]	-	[206][e]
CFCs	653	208	138	7286	17	0	0	8302
HCFCs	1582	1536	42	1696		6	9	4871
HFCs	1922	1488	896	644	23	226	27	5227
PFCs				0		4	0.1	4
Total[e]	**4157**	**3232**	**1076**	**9626**	**40**	**236**	**37**	**18,404**

2015 Mitigation	**Banks (MtCO$_2$-eq yr^{-1})**							
	Refrigeration[a]	SAC[b]	MAC[c]	Foams	Medical aerosols[f]	Fire protection	Other[d,f]	Total
Halons	-	-	-	-	-	[206][e]	-	[206][e]
CFCs	627	208	138	7286	0	0	0	8258
HCFCs	1466	1134	41	1696		6	9	4352
HFCs	1455	1586	712	494	26	226	27	4527
PFCs				0		4	0.1	4
Total[e]	**3548**	**2928**	**891**	**9475**	**26**	**236**	**37**	**17,141**

Notes

[1] 'Refrigeration' comprises domestic, commercial, industrial (including food processing and cold storage) and transportation refrigeration.

[b] 'SAC' (stationary air conditioning) comprises residential and commercial air conditioning and heating.

[c] 'MAC' (mobile air conditioning) applies to cars, buses and passenger compartments of trucks.

[d] 'Other' includes non-medical aerosols and solvents.

[e] Halons cause much larger negative indirect than positive direct radiative forcing and, in the interest of clarity, their effects are not included in the totals and are shown in brackets in the table.

[f] Emissive use applications are assumed to have banks that are equal to annual emissions.

2015 Business-as-usual projections

The sector chapters have developed business-as-usual (BAU) projections for the use and emissions of CFCs, HCFCs, halons, HFCs and some PFCs (where these are used as replacements for ODSs). These projections have assumed that all existing measures will continue, including the Montreal Protocol (phase-out) and relevant national regulations. The usual practices and emission rates are kept unchanged up to 2015. End-of-life recovery efficiency is assumed not to increase. An overview of key assumptions for the BAU projections of 2015 is given in Table TS-6.

Table TS-6. Key assumptions in the business-as-usual (BAU) and mitigation (MIT) scenarios.

Sector	**Annual market growth 2002-2015 (both in BAU and MIT)[1] (% yr^{-1})**				**Best-practice assumptions**								
Refrigeration SAC and MAC	EU % yr^{-1}	USA % yr^{-1}	Japan % yr^{-1}	DCs[1] % yr^{-1}	Type of reduction	EU		USA		Japan		DCs[1]	
						BAU	MIT	BAU	MIT	BAU	MIT	BAU	MIT
Domestic refrigeration	1	2.2	1.6	2–4.8	Substance	HFC-134a / HC-600a	HC-600a	HFC-134a	HFC-134a / HC-600a (50%)	HFC-134a	HC-600a	CFC-12 / HFC-134a	Plus HC-600a (50% in 2010)
					Recovery	0%	80%	0%	80%	0%	80%	0%	50%
Commercial refrigeration	1.8	2.7	1.8	2.6–5.2	Substance	R-404A R 410A	R-404A / R-404A (50%)	HCFC-22 / R-404A /	R-404A / R 410A (50%)	HCFC / R-404A	R-404A R-410A (50%)	CFC / HCFC	R-404A / R 410A (50%)
					Recovery	50%	90%	50%	90%	50%	90%	25%	30%
					Charge		-30%		–30%		–30%		–10%
Industrial refrigeration	1	1	1	3.6–4	Substance	HFC-NH_3 (35%)	HFC-NH_3 (70%)	HCFC / HFC-NH_3 (60%)	HCFC / HFC-NH_3 (80%)	HCFC / HFC-NH_3 (35%)	HCFC / HFC-NH_3 (70%)	CFC / HCFC-22	NH_3 (40–70%)
					Recovery	50%	90%	50%	90%	50%	90%	15–25%	50%
					Charge		–40%		–40%		–40%		–10%
Transport refrigeration	2	3	1	3.3–5.2	Substance	HFCs	HFCs	HCFCs / HFCs	HCFCs / HFCs	HCFCs / HFCs	HCFCs / HFCs	CFC / HCFC-22	Plus HFCs, up tp 30%
					Recovery	50%	80%	50%	70%	50%	70%	0%	20–30%
Stationary AC	3.8	3	1	5.4–6	Substance	HFCs	HFCs	HCFCs / HFCs	HCFCs / HFCs	HCFCs / HFCs	HCFCs / HFCs	CFC / HCFC-22	CFC / HCFC-22 (HFCs 30% in some DCs)
					Recovery	50%	80%	30%	80%	30%	80%	0%	50%
					Charge				–20%		–20%		
Mobile AC	4	4	1	6–8	Substance	HFC-134a / CO_2 (10%) as of 2008	HFC-134a / CO_2 (50%) as of 2008	HFC-134a	HFC-134a / CO_2 (30%) as of 2008	HFC-134a	HFC-134a / CO_2 (30%) as of 2008	CFC / HCFC-134a	CFC / HFC-134a
					Recovery	50%	80%	0%	70%	0%	70%	0%	50%
					Charge	700 g	500 g	900 g	700 g	750 g	500 g	750–900 g	750–900 g

Table TS-6. (continued)

Sector	Annual market growth 2002-2015 (both in BAU and MIT)[1] (% yr^{-1})	Best-practice assumptions	
Foams	About 2% yr^{-1}	BAU	Assumptions on substance use (see Chapter 7)
		MIT	HFC consumption reduction: A linear decrease in use of HFCS between 2010 and 2015 leading to 50% reduction by 2015. Production / installation improvements: The adoption of production emission reduction strategies from 2005 for all block foams and from 2008 in other foam sub-sectors. End-of-life management options: The extension of existing end-of-life measures to all appliances and steel-faced panels by 2010 together with a 20% recovery rate from other building-based foams from 2010.
Medical aerosols	1.5–3% yr^{-1}	BAU	Partial phase-out of CFCs
		MIT	Complete phase-out of CFCs
Fire protection	–4.5% yr^{-1} (all substances) +0.4% yr^{-1} (HCFCs/HFCs/PFCs)	BAU	Phase-out of halons
		MIT	Not quantifiable
HFC-23 byproduct	2.5% yr^{-1}	BAU	HFC-23 emissions of existing production capacity: 2% of HCFC-22 production (in kt) HFC-23 emissions of new production capacity: 4% of HCFC-22 production (in kt)
		MIT	100% implementation of reduction options (90% emission reduction)
Non-medical aerosols	16% increase period in total CO-weighted emissions over 2002–2015	BAU	See Chapter 10
		MIT	Not quantifiable

[1] BAU: Business-As-Usual Scenario; MIT: Mitigation Scenario; DCs: developing countries

The activities underlying the emissions of fluorocarbons are expected to grow significantly between 2002 and 2015. These activities and services (such as refrigeration, air conditioning and insulation) will be provided by a number of technologies and substances, including CFCs and HCFCs. In industrialized countries, the use and emissions of CFCs and HCFCs will decline following the Montreal Protocol phase-out requirement as obsolete equipment is retired. In developing countries, the production of HCFCs can continue until 2040, and significant increase in their production is expected. These changes, and their impacts, are reflected in the data in Table TS-4. [11.6]

The decline in CFC emissions is not accompanied by a similar increase in emissions of HFCs because of continuing trends towards non-HFC technology and substitutes with lower GWPs. In addition, but not included in the BAU scenario, the capture and safe disposal of substances that were emitted in the past are likely to increase with respect to HFCs since these substances are controlled under the Kyoto Protocol. The BAU case assumes the continuing application of all existing measures, and the mitigation scenario embodies improvements that could be implemented assuming global application of current best-practice emission reduction techniques.

In the BAU scenario, banks are projected to decline to 18 $GtCO_2$-eq in 2015. CFC banks associated with refrigeration, SAC[17] and MAC equipment are expected to fall from about 6 $GtCO_2$-eq in 2002 to 1 $GtCO_2$-eq by 2015, mainly due to release to the atmosphere and partly due to end-of-life recovery and destruction. CFC banks in foams remain significant (decreasing from 10 to 7 $GtCO_2$-eq over the same period). HCFC banks will increase from about 4 to 5 $GtCO_2$-eq, primarily due to the projected increase of HCFC-22 use in commercial refrigeration. Total HFC banks will start to build up to 5 $GtCO_2$-eq in 2015. HFC banks in foams represent only 0.6 $GtCO_2$-eq and are projected to increase further after 2015. [11.4 and 11.6]

In the BAU scenario, total direct emissions of CFCs, HCFCs, HFCs and PFCs are projected to represent about 2.3 $GtCO_2$-eq yr^{-1} by 2015 (as compared to about 2.5 $GtCO_2$-eq yr^{-1} in 2002)[16]: Combined CFC and HCFC emissions are decreasing from 2.1 (2002) to 1.2 $GtCO_2$-eq yr^{-1} (2015), and emissions of HFCs are increasing from 0.4 (2002) to 1.2 $GtCO_2$-eq yr^{-1} (2015)[18]. PFC emissions from ODS substitute use are about 0.001 $GtCO_2$-eq yr^{-1} (2002) and projected to decrease.

Table TS-4 shows the relative contribution of sectors to global direct GHG emissions that are related to the use of ODSs and their substitutes. Refrigeration applications together with SAC and MAC contribute the bulk (77% in 2015 BAU) of global direct GHG emissions, which is in line with the higher emission rates associated with refrigerant banks. The largest part of GHG emissions from foams are expected to occur after 2015 because most releases occur at end-of-life. HFC-23 byproduct emissions account for 14% of all direct GHG emissions (2015 BAU).

Due to the leakage of CFCs from banks to the atmosphere, emissions of CFCs will decrease from 1.7 (2002) to 0.3 $GtCO_2$-eq (2015). HCFC emissions are projected to increase from 0.4 (2002) to 0.8 $GtCO_2$-eq yr^{-1} (2015), owing to a steep increase in their use in (commercial) refrigeration and SAC applications. The projected threefold increase in HFC emissions is the result of the increased application of HFCs in the refrigeration, SAC and MAC sectors and due to byproduct emissions of HFC-23 from increased HCFC-22 production. HCFC-22 production is projected to increase by about 40% over the 2002–2015 period. [11.4 and 11.6]

The literature does not allow for an estimate of overall indirect GHG emissions related to energy consumption. For individual applications, the relevance of indirect GHG emissions over a life cycle can range from low to high, and for certain applications may be up to an order of magnitude larger than direct GHG emissions. This is highly dependent on the specific sector and product/application characteristics, the carbon-intensity of the consumed electricity and fuels during the complete life cycle of the application, containment during the use-phase and the end-of-life treatment of the banked substances. Table TS-7 presents examples of the ranges found in the literature with respect to the proportion of direct emissions to total GHG emissions for applications using HFCs. For applications using other substances, these proportions may differ significantly. The relatively old vintage stock of refrigeration equipment using CFCs may, in particular, provide a larger share of direct emissions. [3.2, 4 and 5]

---

[17] In this Technical Summary, the 'refrigeration' sector comprises domestic, commercial, industrial (including food processing and cold storage) and transportation refrigeration. [4] 'Stationary air conditioning (SAC)' comprises residential and commercial air conditioning and heating. [5] 'Mobile air conditioning (MAC)' applies to cars, buses and passenger compartments of trucks.

[18] For these emission values the most recent scientific values for GWPs were used (see Table TS-3). If the UNFCCC GWPs would be used, reported HFC emissions (expressed in tonnes of CO_2-eq) would be about 15% lower.

Table TS-7. Percentage contribution of direct emissions to total lifetime greenhouse gas emissions in various applications (emissions associated to functional unit) – selected indicative examples for applications using HFCs.

Application sector	Method applied	Percentage of HFC emissions of lifetime system greenhouse emissions (using GWP-100)	Characterization of system and key assumptions
MAC	TEWI	**40–60%** – Current systems (gasoline engine) **50–70%** – Current systems (diesel engine)	Passenger vehicle; HFC-134a Sevilla (Spain)
Commercial refrigeration	LCCP	**20–50%** – For a wide range of sensitivity tests on leakage rate, energy efficiency and energy supply	Direct expansion refrigeration unit; supermarket (1000 m^2); R-404A; Germany
Domestic refrigeration	TEWI	**2–3%** – No recovery at end-of-life	European standard domestic refrigerator; HFC-134a; world average electricity mix
Insulation foam of domestic refrigerators	LCCP	**6%** – With 90% blowing agent recovered at disposal **17%** – With 50% blowing agent recovered at disposal	HFC-24fa; Europe
PU insulation foam in refrigerated truck	LCCP	**2%** – With full recovery of HFC at disposal **13%** – without recovery of HFC at disposal	Refrigerated diesel truck; Germany
PU spray foam industrial flat warm roof	LCA	**13%** – With full recovery of HFC at disposal **20%** – without recovery of HFC at disposal	4 cm thickness; HFC-365mfc; Germany
PU boardstock in private building cavity wall	LCA	**4%** – With full recovery of HFC at disposal **17%** – Without recovery of HFC at disposal	5 cm thickness; HFC-365mfc; Germany
PU boardstock in private building pitched warm roof	LCA	**10%** – With full recovery of HFC at disposal **33%** – Without recovery of HFC at disposal	10 cm thickness; HFC-365mfc; Germany

2015 mitigation-scenario projections

Mitigation options are identified and described for each sector in the respective sector chapters. In Section 4 of this Technical Summary, more detailed information on sectoral reduction opportunities is given. On a more aggregated level, overall sector emission reduction potentials are determined for 2015 relative to the BAU scenario. The estimates are based on a mitigation scenario, which assumes the global application of best practices in use, recovery and destruction of ODSs and ODS-substitutes. The scenario assumptions are presented in Table TS-6, and the sectoral GHG emissions in the mitigation scenario in 2015 are shown in Table TS-4.

Through global application of best practices and recovery methods, about 1.2 $GtCO_2$-eq yr^{-1} of direct GHG emissions can be reduced by 2015, as compared with the BAU scenario. About 60% of this potential is HFC emission reduction; HCFCs and CFCs contribute about 30% and 10%, respectively. Almost 75% of the reduction potential can be found in the refrigeration, SAC and MAC sectors, and about 25% can be found in the destruction of HFC-23 byproduct emissions from HCFC-22 production. This latter option represents about 40% of the HFC-reduction potential. [11.6]

Of the bank-related emissions that can be prevented during the period preceding 2015, the bulk is in refrigerant-based applications where BAU emission rates are considerably more significant than they are for foams during the same period. With earlier action, more of the CFC banks can be captured.

Most indirect energy-related GHG emissions occur during the use-phase of the applications and, in many cases, energy efficiency improvements can result in significant reductions in GHG emissions, particularly where the use-phase is long. Energy efficiency improvements can be profitable and reduce the net costs of the emission reduction options, although the reduction potential is again highly dependent on the specific circumstances. While the assessed literature did not allow for a global estimate of this reduction potential, several case studies at the technology and country level illustrate this point.

Uncertainties

Uncertainties in emission projections are significant. A comparison of atmospheric measurements with inventory calculations shows differences per group of substances (CFCs, HCFCs, HFCs and PFCs) in the order of 10–25%. For individual gases, the differences can be much bigger. These differences are caused by unidentified emissive applications of some substances (e.g. CFC-11, HCFC-141b, HCFC-142b) that are not accounted for in inventory calculations and by uncertainties in the geographically distributed data sets of equipment in use. [11.3.4]

3.3 Which options are available for reducing GHG emissions?

In general, technical options to reduce direct GHG emissions can be achieved through:

- improved containment of substances;
- reduced charge of substances in equipment and products;
- end-of-life recovery and recycling or destruction of substances;
- increased use of alternative substances with a reduced or negligible global-warming potential;
- not-in-kind technologies.

Reductions of indirect GHG emissions can be achieved by improving the energy efficiency of products and processes (and by reducing the specific GHG emissions of the energy system). To determine which technology option has the highest GHG emission reduction potential, both direct and indirect emissions have to be assessed. The comparison of technology options is not a straightforward exercise as even within one technological application significant variations in direct and indirect emissions may occur. Figure TS-10 shows the distribution of direct emissions from mobile air conditioners in a fleet of passenger cars and of indirect energy-related emissions from supermarket refrigerators. The graphs show that even within a single technology class considerable differences in potentials usually exist to reduce direct and/or indirect emissions. The proper monitoring, benchmarking and understanding of system performance will be a crucial first step in facilitating short- and mid-term emission reductions. However, to achieve major emission reductions in the long run, choices have to be made between the different established technology options and, consequently, there is a need to be prepared and informed by standardized environmental assessment tools.

3.4 Which assessment tools can provide information on technology choices?

The protection of the stratospheric ozone layer and climate requires the selection of technologies which differ with respect to their impacts on climate, on health, safety and other environmental endpoints and on their private and social costs. Analyses of these various impacts can assist decision-makers to choose among competing replacement technologies. However, the results of such analyses can vary, depending upon which of the many factors that are not intrinsic to the technologies are taken into consideration; these include the analytical approach (e.g. top-down compared with bottom-up), degree of product or process optimization, service and disposal practices, regional circumstances and a wealth of other inputs and assumptions. To make intelligent choices, decision-makers must therefore be aware of the sensitivities, uncertainties and limitations inherent in each type of analysis and must also be able to evaluate whether the approach and assumptions used in an analysis are reasonable for the regions

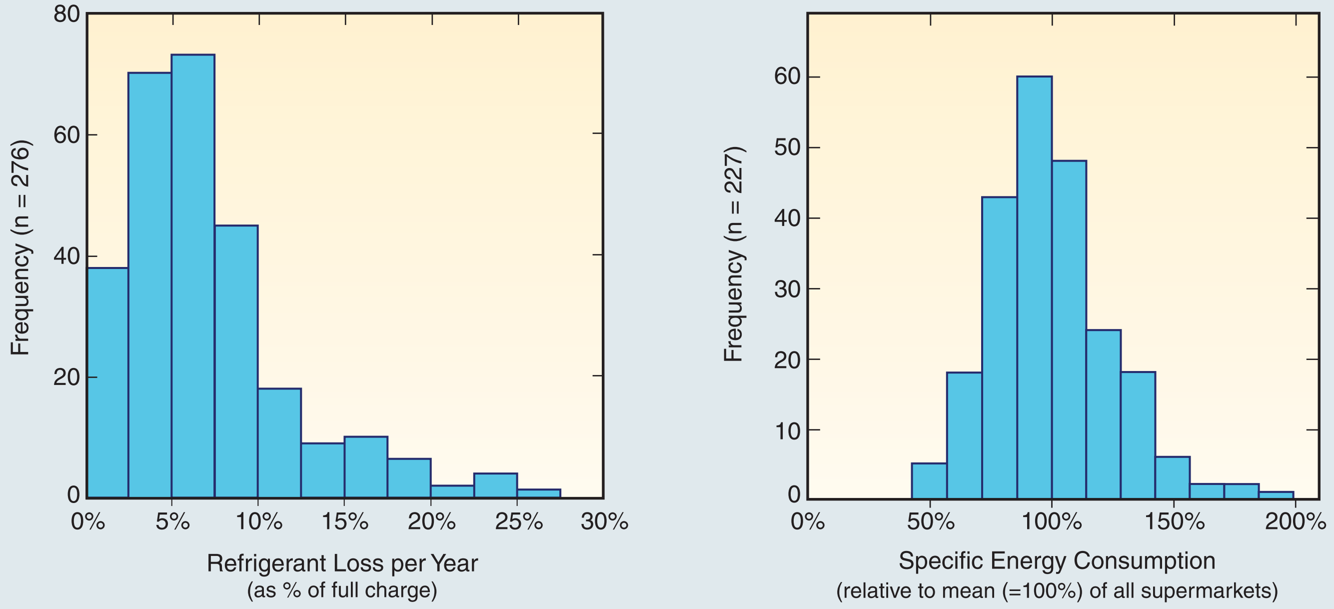


Figure TS-10. Variance of direct and indirect emissions within equipment populations. Annual leakage rates of mobile air conditioning systems in a fleet of passenger vehicles (left panel, n=276). Specific energy consumptions expressed as percentage of the mean for a group of standard layout supermarket refrigeration units (right panel, n=227).

and time periods in which the competing technologies would be applied.

To face such challenges, well-established and clearly described methodologies are needed. This report provides an overview of the different types of analyses and provides concise guidance on how to evaluate and apply them. For each type of analysis, the most important analytical approaches and variables are discussed, along with their sensitivities, uncertainties and limitations.

Any assessment of technical options to reduce the impacts of emissions involves the evaluation of multiple factors. These include the influence of direct and indirect emissions on radiative forcing, costs, health, safety and environmental impacts for each application and compound; service or design practices that can lead to reduced leakage; the effects of recovery and recycling. These factors may be subject to large uncertainties and differ from application to application and region to region. Non-technical factors also need to be considered, such as differing regulatory and management environments in different parts of the world, the availability of infrastructure, investment financing and historical factors. In many cases, only incomplete information on these factors is available, thereby limiting the comprehensiveness of the assessment.

This report deals with direct emissions of halocarbons that are associated with their production, use and decommissioning as well as indirect emissions due to energy requirements. Such emissions are quantified and costs associated with their reduction are evaluated according to methodologies presented herein. For a comprehensive assessment, not only private costs need to be quantified: also external costs that are not paid by the private sector but which are a burden to society should be accounted for.

The purpose of the methodologies chapter in this report (Chapter 3) is to describe procedures for quantifying both ODS and GHG emissions and the costs associated with reducing these emissions. A broad spectrum of assessment tools exists, ranging from tools with very well-established procedures applicable at global level to those loosely defined and not applied in a consistent manner. Table TS-8 provides an overview of methodologies identified as being relevant to this report.

In assessing environmental and climate change impacts, decision-makers prefer to have a comprehensive picture of all relevant environmental aspects. However, information other than that on direct and indirect GHG emissions is often difficult to quantify. Consequently, Total Equivalent Warming Impact (TEWI, a measure of GHG emissions during the use-phase and disposal) and Life Cycle Climate Performance (LCCP, which also includes the direct GHG emissions during manufacture and the indirect GHG emissions that are associated with the embodied energy of the substances of concern) have more practical value than more encompassing methodologies like Life Cycle Assessment (LCA), Environmental Burden and others. It is worth noting that there is no scientifically established basis for reducing multiple impact results (like LCA) to a single overall score or number.

In the past, little attention was paid to ensure the comparability of results from different technology assessments. There is a wide range of available results on GHG performance from different assessments – often not comparable. The treatment of uncertainties is often incomplete, and resulting recommendations are not sufficiently robust to be compared across sectors. In the light of the many assumptions and different methodologies, an important role has been identified for technology comparisons under agreed conditions using a common set of methods and assumptions. The development of simple and pragmatic standard methodologies and their respective quality criteria is recommended. Future work will need to bridge the gap between the application of specific comparisons and sufficiently robust results that can be used for policy design in entire subsectors.

Analyses of sectoral and global emissions and emission reduction potentials are based on extensive databases on equipment populations and other product distributions that comprise field data on substance emissions and energy consumption. These databases should ideally be consistent and compatible with national GHG emission inventories. Information on fluid sales to the different parties involved in the subsector will need to be made available. The improvement of these fairly comprehensive data sets for analysis in support of robust sectoral policies requires significant resources and results in a number of confidentiality issues which need to be addressed cautiously. To achieve acceptability across subsectors with respect to future developments, decision-makers could consider paying special attention to increasing the involvement of relevant stakeholders and to introducing additional measures in order to increase transparency for outside users through more extensive documentation of methods and assumptions.

Table TS-8. Overview of assessment methodologies reviewed in this report.

Methodology to assess	Overview
Direct emissions	
Production	1) Identification of all feedstock requirements and chemical processing stages necessary to transform feedstock to intermediaries and final product. 2) Accounting for all emissions occurring at each stage through measurement and/or modelling.
Use	1) Measurements to estimate losses of fluids during lifetime of equipment, which yield direct emissions. 2) Transportation and distribution losses are included as direct use emissions.
Decommissioning	1) Emissions are accounted for based on the final destination of the products. 2) If no recovery, all remaining fluids are assumed to be direct emissions. 3) If recovered, emissions may also occur during fluid reprocessing.
Indirect emissions	
Production	1) Modelling and/or measurement of built-in energy in equipment used for feedstock sourcing, preprocessing, transport and transformation to final product in the plants. 2) Modelling and/or measurements of total energy consumption to produce one unit of a particular fluid from feedstocks. 3) Relating energy consumption to emission of GHGs through region- or country-specific data.
Use	1) Energy consumption evaluation during equipment lifetime. a) Refrigeration, air conditioning and heating applications: modelling and/or measuring equipment energy consumption. b) Insulating foams: b1) Thickness compensation modelling and/or b2) measuring energy consumption for baseline and for foam insulated application. 2) Relating energy consumption to emission of GHGs through region- or country-specific data.
Decommissioning	1) Energy consumption required for product recycling or destruction at end-of-life. 2) Relating energy consumption to emission of GHGs through region- or country-specific data.
Costs	
Private costs	Costs are calculated based on expertise of private companies. These mainly include capital costs, labour, land, materials, maintenance and administrative costs.
Social costs	Costs usually charged to society, such as air and water pollution, associated with production of goods by private sectors. Costs are estimated through the quantification of benefits and damages induced by final product.
Discount rates	Use this to consider different time distribution of costs incurred. Present value or levelized cost is evaluated taking into consideration market or social discount rates for private or social costs, respectively.
Sustainable development	Quantification, or at least qualification, of positive and negative impacts caused on a society's well-being by changes in production and use of fluids.
Health and safety	
Health and safety	1) Focus on risk assessment of chemicals and then minimising the negative health and safety impacts through risk management of systems. 2) For relevant substances use the references to existing databases and data sources.
Environmental impacts	
TEWI (Total Equivalent Warming Impact) – Accounts for GHGs from direct emissions of operating fluids together with the energy-related CO_2	$TEWI = \sum(a_i*b_i + a_i*c_i) + d$ a_i = GWP of gas *i* emitted; b_i = mass of gas *i* released during the operating lifetime of the system; c_i = mass of gas *i* released when the system is decommissioned at end-of-life; d = emission of CO_2 resulting from the energy used to operate the system (for its entire lifetime).
LCCP (Life Cycle Climate Performance) – Accounts for TEWI factors plus the fugitive emissions arising during manufacture (of the operating fluids only) and the CO_2 associated with their embodied energy.	$LCCP = TEWI$ (calculated value as above described) $+ \sum x_i*y_i + z$ x_i = GWP of gas *i* emitted during the manufacture of fluid; y_i = mass of gas *i* released during the manufacture of fluid; z = embodied energy of all material used for the manufacture of fluid (the specific energy used for the manufacture of one unit mass of each material multiplied by the total mass emitted) expressed in CO_2-eq.
LCA (Life Cycle Assessment) – Describes the environmental impacts of product systems from raw material acquisition to final disposal	1) Describe the system in terms of its unit processes and their interrelationships. 2) Compile an inventory of relevant inputs and outputs of each unit process and of the systems that are involved in those inputs and outputs (Life Cycle Inventory Analysis). 3) Evaluate potential environmental impacts of these inputs and outputs. The most obvious environmental impact categories are climate change and ozone depletion, but some or all of the environmental categories may be important.

3.5 What are regional differences?

Difference in economic development is a very important factor explaining regional differences in assessments. Key assumptions on technical performance indicators, such as equipment lifetime and operational cost of equipment and products, vary greatly from developed to developing countries in ways that seem to be related with the cost of capital.

In developing countries, traditional private costs are usually accounted for, while other hidden private costs (e.g. for Research and Development (R&D), training, environmental liability) are seldom considered. External costs are generally poorly accounted for because there are usually no regulations in place to deal with externality issues and the awareness amongst the population is low. On-site health and safety regulations are usually taken into consideration due to the existence and enforcement of labour laws in most developing countries.

Between developed and developing countries significant variations can also be found with respect to the uncertainty range of their emission estimates (both direct and indirect emissions), which in turn are used as input for further analysis. In the case of direct emissions, some progress has been made in the diffusion of emission inventory methodologies under the Montreal Protocol Multilateral Fund investments in developing countries. However, for both developed and developing countries, uncertainties are generally significant. Improving the quantification of indirect GHG emissions, which are significant relative to total GHG emissions, remains a challenge for all countries. Difficulties centre around such issues as data availability on energy consumption, determination of the carbon intensity of the energy consumed and the GHG emission estimates related to the embodied energy in production inputs. These challenges point to the necessity for a concerted global effort if decision-makers are to be provided with the information needed to make decisions supportive of global ozone layer and climate policies.

The above challenges are compounded by the fact that each technology that results in direct or indirect emissions has unique data requirements for determining their climate and ozone impacts. This situation raises issues of capacity, standards, policy and regulation, for which developed countries have established better, though not comprehensive, frameworks within which to respond. This emphasizes the need to develop simple, standard methodologies and the respective quality criteria, as recommended in the report. [3.6]

3.6 What major opportunities have been identified for reducing GHG emissions associated with the use of ODSs, their substitutes and related indirect emissions?

The major opportunities for reducing direct emissions in terms per sector and per substance group are quantified in Table TS-4. Table TS-9 summarizes the sector characteristics and specific mitigation opportunities. In Section 4 of this Technical Summary, the opportunities for reducing GHG emissions are discussed in more detail.

Table TS-9. Overview of sector- and application-specific findings.

Sector	Description and status of sector	Emission status and BAU trends and opportunities for emissions reduction
Domestic refrigeration	• Manufacturing transitions from CFC-12 are complete in developed countries and in progress in developing countries	Emission status and BAU trends • Refrigerant leakage rates derived with a bottom-up approach suggest a global annual emissions rate of 6% of banked system charge, caused by the significant bank of CFCs in old equipment. New non-CFC systems have typical leakage rates of about 1% yr^{-1}. • The projected emissions in this subsector by 2015 are about 65 $MtCO_2$-eq yr^{-1} in the BAU-scenario. Opportunities for emissions reduction • HFC-134a and isobutane (HC-600a) are the primary alternative refrigerants for the previously used CFC-12. Each has demonstrated a mass production capability for safe, efficient, reliable and economic use. The choice of HFC-134a or HC-600a varies per region and is strongly influenced by the regulatory environment and liability. • For both refrigerants, indirect emissions dominate total emissions, almost without taking the carbon intensity of electric power generation into consideration. At equal energy efficiencies, HC-600a domestic refrigerators have a better LCCP, with or without end-of-life recovery. The difference with HFC-134a is small, and end-of-life recovery can further reduce the magnitude of the difference. • State-of-the-art refrigeration products are at least 50% more energy-efficient than the 20-year-old units they typically replace.
Commercial refrigeration	• Commercial refrigeration comprises three main types of equipment: stand-alone equipment, condensing units and full supermarket systems. • The most used refrigerants in this sector are HCFC-22, R-404A and HFC-134a.	Emissions status and BAU trends • Refrigerant leakage rates derived with a bottom-up approach suggest a global annual emissions rate of 30% of banked system charge, meaning that the refrigerant emissions typically represent 60% of the total emissions of GHGs resulting from the system operation. • Refrigerant leakage rate data from over 1700 full supermarket systems in USA and Europe were in the range of 3–22%, with an average of 18%. • In 2002, all refrigerant types banked in commercial refrigeration equipment – predominantly CFCs, HCFCs and HFCs – represented 606 ktonnes of a total of 2691 ktonnes for all refrigerating and air conditioning (AC) systems and all refrigerant types, which is 22.5% of the total refrigeration and AC bank. • The projected emissions by 2015 in this subsector are about 902 $MtCO_2$-eq yr^{-1} in the BAU-scenario. Opportunities for emissions reduction • Significant total emission reductions, that is improved LCCP, can be achieved by using refrigerants HFCs, hydrocarbons, ammonia or CO_2, employing charge reduction, more efficient containment and overall improved energy efficiency through new system designs. • In full supermarket systems, LCCP values up to 60% lower than centralized direct systems of traditional design can be obtained by applying direct systems using alterative refrigerants, better containment, distributed systems, indirect systems or cascade systems. Published results show alternatives to have 0–35% higher initial cost and an energy usage 0–20% higher than that of current systems. • Refrigerant emissions abatement cost was found to be in the range of 20–280 US$ per tCO_2-eq (10% yr^{-1} discount rate). Development work on new systems is continuing to reduce cost and energy usage in these systems. This will further reduce the abatement costs. Taking a possible increase in energy efficiency into consideration may also result in negative abatement costs (savings). • For small commercial units, namely stand-alone equipment and condensing units (vending machines, ice-cream freezers, walk-in coolers, etc.), global companies have begun employing low- or zero-GWP alternatives to HFCs (hydrocarbons and CO_2) and alternative technologies, which promise reduced direct and comparable or lower indirect emissions.

Table TS-9. (2) Overview of sector- and application-specific findings.

Sector	Description and status of sector	Emission status and BAU trends and opportunities for emissions reduction
Food processing, cold storage and industrial refrigeration	• This broad sector comprises refrigeration equipment for chilled and frozen food processing and storage, plus industrial applications in the chemical, oil and gas industries, air liquefaction and industrial and recreational-facility ice making. • Refrigerants predominantly used in this sector are ammonia and HCFC-22, with smaller amounts of CFCs and HFCs; hydrocarbons are used in the petrochemical industry.	Emissions status and BAU trends • In 2002, all refrigerant types banked in this sector amounted to 298 ktonnes (35% ammonia and 43% HCFC-22). Annual refrigerant emissions were 17% of banked system charge. • The projected emissions in this subsector by 2015 are about 104 $MtCO_2$-eq yr^{-1} in the BAU-scenario. Opportunities for emissions reduction • Ammonia is forecast for increased use in the future, with HFCs 404A, 507A, 410A and 134a replacing HCFC-22 and CFCs. CO_2 and ammonia/CO_2 cascade systems are beginning to be used in applications having evaporator temperatures of –40°C and lower. • Significant total emission reductions can be achieved by using lower GWP refrigerants, employing system refrigerant charge reduction, more efficient containment, improved refrigerant recovery and overall improved energy efficiency through new system designs. LCCP calculations are used to optimize refrigerant choice and system design for the lowest environmental impact. • The abatement costs of refrigerant emissions from industrial refrigeration were determined to be in the range of 27–37 US$ (2002) per tCO_2-eq (8% yr^{-1} discount rate).
Transport refrigeration	• The transport refrigeration sector consists of systems for transporting chilled or frozen goods by road, rail, sea and air. Current systems use refrigerants CFC-12, R-502 (a CFC/HCFC blend), HCFC-22, HFCs (HFC-134a, R-404A, R-507A, R-410A, and R-407C) and smaller amounts of ammonia, hydrocarbons and CO_2 in vapour compression systems. Ice and liquid or solid CO_2 are also used for refrigeration in this sector. • Several types of refrigeration configurations are used, such as shipboard systems, containers with individual refrigeration units which can be transported by sea, rail or road, and refrigerated trucks and railcars. Air transport refrigeration is mainly with ice or solid CO_2.	Emissions status and BAU trends • Relatively severe operating environments such as exposure to outdoor conditions of high or low temperatures, high humidity, salt-water corrosion, road vibrations and container-handling shocks lead to refrigerant leakage rates of 25–35% yr^{-1}. • The projected emissions in this subsector by 2015 are about 22 $MtCO_2$-eq yr^{-1} in the BAU-scenario. Opportunities for emissions reduction • Better containment of refrigerants by improved system design, one example being the recent application of low-leakage hermetic compressor systems for road transport and container refrigeration. • Reduced energy consumption via improved insulation, compressor motor frequency control for partial load conditions, water-cooled condensers for shipboard systems and preventive maintenance to reduce heat exchanger fouling. • Use refrigerants with lower GWP, examples being ammonia or ammonia/CO_2 systems for ship refrigeration and hydrocarbon or CO_2 vapour-compression systems for road, rail and container refrigeration. Considerations for using these refrigerants compared with fluorocarbon systems include safety requirements, system costs of energy efficiency, and the status of commercialization. CO_2 systems are still in the testing and demonstration stages.
Stationary air conditioning and heat-pumps	• 'Stationary air conditioning (SAC) and heat pumps' comprises unitary air conditioners (window-mounted, split systems), cold-water centralized AC systems (chillers) and water-heating heat pumps. • HCFC-22 is the most widely used refrigerant for air-to-air systems. HFC blends were used for the first time on a significant scale in Europe and Japan. Globally, 90% of air conditioners are still produced with HCFC-22. In the past 5 years, China has become the largest producer and consumer of AC units in the world. Chinese production is approximately equal to the annual global production in the rest of the world. • Currently, most of centrifugal chillers sold use HCFC-123 and HFC-134a.	Emissions status and BAU trends • Smaller chillers using positive displacement compressors generally employed HCFC-22 as the refrigerant. This refrigerant is being replaced by HFC-134a, HFC blends and, to a lesser extent, by ammonia and hydrocarbons. • The projected emissions in this sector by 2015 are about 370 $MtCO_2$-eq yr^{-} in the BAU-scenario. Opportunities for emissions reduction • Improving the integrity of the building envelope (reduced heat gain or loss) can have a very significant impact on indirect emissions. • HFC mixtures (R-407C and R-410A) and hydrocarbons (for small systems, mainly portable, in Europe) are used as alternatives for HCFC-22 in developed countries. For those applications for which hydrocarbons can be safely applied, the energy efficiency is comparable to HCFC-22 and R-410A. Future technical developments could reduce refrigerant charge, thereby expanding the applicability of hydrocarbons.

Table TS-9. (3) Overview of sector- and application-specific findings.

Sector	Description and status of sector	Emission status and BAU trends and opportunities for emissions reduction
Stationary air conditioning and heat-pumps (cont.)	• CFC (centrifugal) chiller manufacture was halted globally in 1993, but about 50% of centrifugal units still use CFC-11 and 12 due to the long lifetime of the equipment. • Commercial and residential AC and heating consumes significant quantities of electrical power with associated indirect GHG emissions and a use-pattern that usually coincides with typical electricity peak demand periods. They account for more than 50% of building energy use in some tropical climates. In most cases, the indirect energy related GHG emissions far outweigh the direct emissions of the refrigerant.	Opportunities for emissions reduction (cont.) • The application limits for hydrocarbons are defined by national and international standards, regulations and building codes. • Residential heat pumps represent significant opportunities to lower energy consumption for building heating. CO_2 has particular advantages for tap-water-heating heat pumps because it benefits from the use of counter-flow heat exchange and high operating temperatures. • High-efficiency equipment is available in markets where both AC/chiller market volumes and electricity prices are high. Compared to the average installed base, substantive improvements can therefore be attained: for example, up to 33% energy reduction. • Specific costs of abatement options range from –3 to 170 US$ per tCO_2-eq. Improved system energy efficiencies can significantly reduce indirect GHG emissions, leading in some cases to overall costs of –75 US$ per tCO_2-eq.
Mobile Air Conditioning	• Mobile Air Conditioning (MAC) systems have been mass-produced in the US since the early 1960s and since the 1970s in Japan. The main refrigerant was CFC-12. The significant increase in the numbers of air-conditioned cars in Europe began later, around 1995, with the introduction of HFC-134a use.	Emissions status and BAU trends • The projected emissions in this subsector by 2015 are about 315 $MtCO_2$-eq yr^{-1} in the BAU scenario. Opportunities for emissions reduction • Options to reduce direct GHG impacts of MACs are: (1) switch to low-GWP refrigerants; (2) better containment of HFC-134a; (3) increase efficiency and reduce cooling load. • HFC-152a and CO_2 (R-744) are the two main options to replace HFC-134a. HFC-152a, apart from its flammability, is largely similar to existing HFC-134a technology. CO_2 systems require newly-developed components and technology. No motor vehicle manufacturer is considering hydrocarbons as an option for new vehicles, but hydrocarbons are in use as service refrigerants in several countries against manufacturers' recommendations (and often against regulations). • Improved HFC-134a systems show a reduction of direct GHG emissions by 50%, HFC-152a systems by 92% and CO_2 systems by nearly 100% on a CO_2-equivalent basis relative to the current HFC-134a systems. • It is technically and economically feasible to reduce indirect emissions through higher system energy efficiency and reduced heat load, regardless of the refrigerant chosen. • There is currently no significant difference between the technically achievable LCCP for HFC-152a and CO_2 systems. • Barriers to commercialization of HFC-152a and CO_2 are the required resolution of: o the flammability risk and assurance of commercial supply of the refrigerant for HFC-152a; o the suffocation risk; o the residual technical and cost issues for CO_2 technology. • Reference cost of a typical European HFC-134a system is evaluated at about US$ 215 with an internal control compressor. Additional cost of a CO_2 system is evaluated between US$ 48 and US$ 180. Additional cost of a HFC-152a system is evaluated at US$ 48 for an added safety system.

Table TS-9. (4) Overview of sector- and application-specific findings.

Sector	Description and status of sector	Emission status and BAU trends and opportunities for emissions reduction
Foams	• Foams fall into two main categories – insulating (buildings, appliances, cold storage, etc.) and non-insulating (bedding, furniture, packaging, safety, etc.) foams. • Not-in-kind materials such as mineral fibre have held a majority share of the thermal insulation market for the past 40 years. However, foam-based insulation solutions have gained a market share over the past 15 years driven, in part, by increasing trends towards prefabrication, where structural integrity and lightweight characteristics are important. Longevity of thermal performance is also of increasing importance. However, investment cost and fire performance continue to support mineral fibre as the major component of most thermal insulation markets.	<u>Emissions status and BAU trends</u> • Manufacturing safety considerations result in the use of HFC blowing agents for smaller companies, where safety investments have a proportionally higher impact on product cost. Product safety can lead to HFC choice for certain applications in buildings, particularly where insurance concerns exist. • For non-insulating rigid and flexible foams, non-halocarbon blowing agents are now widely used. Hydrocarbon and CO_2 (both liquid- and water-based) technologies have been demonstrated to be as technically viable in a variety of foam categories, implying very little continuing global halocarbon consumption for this category. • The projected emissions by 2015 in this sector are about 124 $MtCO_2$-eq yr^{-1} in the BAU-scenario. <u>Opportunities for emissions reduction</u> • Insulating foams are expected to contribute significantly to CO_2 emission reductions in buildings and appliances as energy-efficiency improvements are demanded. Blowing-agent selection can affect thermal performance significantly. • LCCP analyses can provide insight when comparing insulation types. However, calculations are very sensitive to the carbon intensity of energy used, the product lifetime assumed, the thickness of insulation and the degree of end-of-life recovery/destruction. • By 2015, hydrocarbons are projected to be the major blowing agent in use within the rigid foam sector, when they are expected to account for nearly 60% of total consumption. Other more modest uses will be HFCs (24%) and HCFCs (16%). The HCFC use will be confined to developing countries where most use will be in appliances. Current HFC estimates of future use are lower than previously predicted, primarily because of high HFC costs. Co-blowing with CO_2 has emerged as an important means of limiting HFC use in some key applications. • Actions to reduce HFC use by 50% between 2010 and 2015 would result in an emission reduction of about 10 $MtCO_2$-eq yr^{-1}, with further increases thereafter, at a cost of 15–100 US$ per tCO_2-eq • Although the effectiveness of recovery has yet to be proven, particularly in the buildings sector, commercial operations are already recovering at 10–50 US$ per tCO_2-eq for appliances. Emission reductions may be about 7 $MtCO_2$-eq yr^{-1} in 2015. However, this potential could increase significantly in the period between 2030 and 2050, when large quantities of building insulation foams will be decommissioned.
Medical aerosols	• Asthma and chronic obstructive pulmonary disease (COPD) are major illnesses affecting over 300 million people worldwide. Metered dose inhalers (MDIs) are the dominant treatment. Dry powder inhalers (DPIs) which do not contain propellants have become more widely available, but are not suitable for all patients and are more expensive.	<u>Emissions status and BAU trends</u> • The projected emissions by 2015 in this sector are about 40 $MtCO_2$-eq yr^{-1} in the BAU scenario. • No major breakthroughs for inhaled drug delivery are anticipated in the next 10–15 years given the current status of technologies and the development time scales involved. <u>Opportunities for emissions reduction</u> • The major impact in reducing GHG emissions with respect to MDIs is the completion of the transition from CFC to HFC MDIs beyond the BAU trend (17 $MtCO_2$-eq yr^{-1} by 2015). • The health and safety of the patient is of paramount importance in treatment decisions and in policymaking that might impact those decisions. This may constrain the use of DPIs. • Based on the hypothetical case of switching the most widely used inhaled medicine (salbutamol) from HFC MDIs to DPI, which would lead to a modest reduction of about 10 $MtCO_2$ eq yr^{-1}, the projected recurring annual costs would be in the order of $1.7 billion with an effective mitigation cost of 150–300 US$ per tCO_2-eq.

Table TS-9. (5) Overview of sector- and application-specific findings.

Sector	Description and status of sector	Emission status and BAU trends and opportunities for emissions reduction
Fire protection	• 75% of original halon use has been switched to agents with no climate impact. 4% of the original halon applications continue to employ halons. The remaining 21% has been switched to HFCs and a small number of applications have been switched to PFCs and HCFCs. • HFCs and inert gases have evolved as the most commonly used gaseous agents and have achieved a degree of equilibrium in terms of market applications and share. • A new FK with nearly zero climate impact has been commercialized, but there is no basis for quantifying its market acceptance.	Emissions status and BAU trends • The projected emissions in this sector by 2015 are about 5 $MtCO_2$-eq yr^{-1} in the BAU-scenario (excluding halons). • Cost remains the main factor in limiting the market acceptance of HFCs, HCFCs and PFCs in portable extinguishers when compared to alternative extinguishers employing more traditional extinguishing agents, such as CO_2, dry chemicals and water. PFC use is currently limited to a minor component in one HCFC-containing blend. Opportunities for emissions reduction • Halons and HFCs are the only available alternatives in a number of fixed-system applications when safety, space and weight, cost, speed of extinguishment and special capabilities, such as those that operate in very cold conditions and on board military ships and vehicles, are taken into account. PFCs and HCFCs offer no advantage over other alternatives. A new low-GWP fluoroketone (FK), not yet tested in specialized applications, will provide additional choices in the future with lower climate impact at an additional cost. Due to the lengthy process of testing, approval and market acceptance of new fire protection equipment types and agents, no additional options are likely to have appreciable impact by 2015. • When possible, the use of agents with no climate effect can reduce GHG emissions from this sector, provided that their use meets the requirements of the specific fire-protection application in a cost-effective manner. • Management of halon, HFC, HCFC and PFC banks requires special attention so that economic incentives are created which ensure that policy intention (e.g. mandatory decommissioning) is achieved. • Implementing responsible-agent management practices will reduce annual emissions from fixed system banks to 2 ± 1% and from portable extinguisher banks to 4 ± 2%.
Non-medical aerosol products	• This sector includes technical, safety, consumer and novelty aerosols. • More than 98% of non-medical aerosols in developed countries have converted from CFCs to ozone- and climate-safe alternatives. • The largest single use of HFCs in non-medical aerosol products is for 'dusters', where pressurized gas is used to blow particles from work surfaces and devices.	Emissions status and BAU trends • The projected emissions in this sector by 2015 are about 23 $MtCO_2$-eq yr^{-1} in the BAU-scenario. Opportunities for emissions reduction • The reduction potential is uncertain but estimated to be rather small. • Substitution of HFC-134a by HFC-152a in technical aerosol dusters is a leading option for reducing GHG emissions. For contact cleaners and plastic-casting mould release agents, the substitution of HCFCs by HFEs and HFCs with lower GWPs offers an opportunity for emission reduction. Safety aerosol products, where flammable propellants and ingredients cannot be used, continue to rely on HFC-134a for its non-flammability. Some countries have banned HFC use in novelty aerosol products. HFC-134a continues to be used in many countries for safety reasons.

Table TS-9. (6) Overview of sector- and application-specific findings.

Sector	Description and status of sector	Emission status and BAU trends and opportunities for emissions reduction
Solvents	• Prior to the Montreal Protocol, CFC-113 and methyl chloroform were widely used as cleaning solvents for metals, electronics, precision and fabric applications. ODS use in these applications has been eliminated or dramatically reduced. Most cleaning solvent applications now rely on not-in-kind substitutes. A small percentage have or are expected to transition to HFCs or HFEs. PFC use is declining and expected to be eliminated by 2025.	Emissions status and BAU trends • The projected emissions in this sector by 2015 are about 14 $MtCO_2$-eq yr^{-1} in the BAU-scenario. Opportunities for emissions reduction • A variety of organic solvents can replace HFCs, PFCs and ODSs in many applications. • These alternative fluids include lower GWP compounds such as traditional chlorinated solvents, hydrofluoroethers (HFEs), and n-propyl bromide. Numerous not-in-kind technologies, including hydrocarbon and oxygenated solvents, are also viable alternatives in some applications. • Safety, especially toxicity, plays a key role in the choice of solvents. Caution is warranted prior to adoption of any alternatives whose toxicity profile is not complete. • HFC solvents are primarily used in technically-demanding specialty applications and then only in selected countries. Uses tend to be focused in critical applications where there are no other substitutes. Consumption may decline in the future. • Use of PFC solvent is constrained to a few niche applications due to the limited solvency, high cost and substitution with lower GWP solvents. • Improved containment is important in existing uses because optimized equipment can reduce solvent consumption by as much as 80% in some applications. Due to their high cost and ease of purification during recycling, fluorinated solvents can be and often are recovered and reused.
HFC-23 byproduct	• HFC-23 is a byproduct of HCFC-22 manufacturing • Although the production of HCFC-22 for direct use is ending in developed countries and will eventually end in developing countries, its production as a feedstock is projected to continue to grow.	Emissions status and BAU trends • The projected emissions by 2015 in this sector are about 332 $MtCO_2$-eq yr^{-1} in the BAU-scenario. • The upper bound of HFC-23 emissions is in the order of 4% of HCFC-22 production. Process optimization can reduce average emissions to 2% or less. However, the actual reduction achieved is facility-specific. Opportunities for emissions reduction • Capture and destruction of HFC-23 by thermal oxidation is a highly effective option for reducing emissions at specific costs below 0.2 US$ per tCO_2-eq. Emissions can be reduced by more than 90%.

3.7 Which policy instruments are available to achieve the reductions in the emissions of GHGs addressed in this report?

As discussed in the IPCC Third Assessment Report, a wide range of policies, measures and instruments can be used to reduce GHG emissions. These include:
- regulations (e.g. mandatory technology and performance standards; product bans);
- financial incentives (e.g. taxes on emissions, production, import or consumption; subsidies and direct government spending and investment; deposit-refund systems; tradable and non-tradable permits);
- voluntary agreements.

Almost all of the policy instrument categories mentioned above have been considered for, or implemented in, reducing the use or emissions of ODSs and their substitutes, such as HFCs and PFCs. Furthermore, general energy or climate policies affect the indirect GHG emissions of applications with ODSs, their substitutes or not-in-kind alternatives. In addition, specific policies for reducing the GHG emissions of ODS substitutes (i.e. HFCs and PFCs) have been formulated. Examples are given in Table TS-10.

3.8 What can be said about the future availability of HFCs/PFCs for use in developing countries?

No published data are available to project future production capacity. However, as there are no technical or legal limits to HFC and PFC production, it can be assumed that the global production capacity will generally continue to satisfy or exceed demand. Future production is therefore estimated in this report by aggregating sectoral demand.

In the BAU scenario, global production capacity is expected to expand with additions taking place mainly in developing countries and through joint ventures. Global production capacity of HFCs and PFCs most often exceeds current demand. There are a number of HFC-134a plants in developed countries and one plant in a developing country with others planned; the few plants for other HFCs are almost exclusively in developed countries. The proposed European Community phase-out of HFC-134a in mobile air conditioners in new cars and the industry voluntary programme to reduce their HFC-134a emissions by 50% will affect demand and production capacity and output. Rapidly expanding markets in developing countries, in particular for replacements for CFCs, is resulting in new capacity for fluorinated gases which is at present being satisfied through the expansion of HCFC-22 and 141b capacity. [11]

Table TS-10. Policy instruments for reducing GHG emissions of ODS-substitutes.

Type of instrument	Specific instrument examples
Regulations	Mandatory performance standards: Energy-efficiency performance standards and leak-tightness performance standards are in place in several countries, notably for refrigeration and cooling applications. Regulations that prohibit venting and require recycling have been enacted in many countries but are often difficult to enforce. Effective application requires complementary compliance programmes and mandatory training of technicians. Vehicle emission performance standards (e.g. restriction of the amount of GHGs emitted by cars, including both fuel and MAC emissions) are being considered (e.g. by the State of California).
	Obligation to use certified companies for servicing of installations and equipment (e.g. 'STEK' programme in the Netherlands).
	Bans and restrictions on the use of specific substances for certain applications: HFCs phase-out schemes are in place or proposed in several countries (e.g. Austria, Denmark, Switzerland). The proposed EU Directive aims to amend the existing EU Vehicle Type Approval legislation which will introduce a GWP threshold for HFCs used in MAC.
	End-of-life management measures, such as mandatory recycling and bans on venting
Financial incentives and market mechanisms	The relative costs of HFCs/PFCs and other alternatives to ODSs will impact the choices of both the users and the producers of these substances. HFCs and PFCs are complex chemicals, and they tend to be more expensive than the ODSs they replace, thus further encouraging the substitution to not-in-kind alternatives. Financial incentives can further shape this cost differential between substances and technologies.
	Deposits or taxes on HFC import and production are collected by several countries. Deposits and taxes raise the cost of HFCs, encouraging containment and making recycling more attractive.
	Tax rebates for delivery of used HFCs and PFCs to destruction facilities provide incentives to minimize emissions. In Norway rebates are NKr 183 (26 US$) per tCO_2-eq
	Subsidies: In addition to the international grants from the Multilateral Fund under the Montreal Protocol and, for example, the Global Environment Facility, national governments subsidize research and development as well as the implementation of new, low-GHG emission technologies. Subsidy (50%) on the cost of collection and destruction of halons and CFCs was provided in the Netherlands to discourage venting, just before stocks of these substances became illegal in 2004.
	Emission reduction of HFCs and PFCs can be funded by the Clean Development Mechanism (CDM) of the Kyoto Protocol. CDM projects exist for Korea and China and are under development for India and Mexico.
	Large point sources of HFCs may be included in emission trading schemes. To date, these sources (e.g. the HFC-23 byproduct emissions of HCFC-22 production) have not usually been included in emissions trading schemes, although the UK scheme is a notable exception. Monitoring the use and emissions of such substances may be less practical for the more diffuse emission sources.
Voluntary agreements	There are several industry- and government-sponsored emission reduction and responsible use programmes. Adherence to responsible use principles can lead to reductions in HFC emissions beyond current projections. Principles for responsible use include: • Use HFCs only in applications where they provide safety, energy efficiency, environmental or critical economic or public health advantage; • Limit emissions of HFCs to the lowest practical level during manufacture, use and disposal of equipment and products; • If HFCs are to be used, select the compound or system with the smaller climate impact that satisfies the application requirements.
	Good practice guidelines have been developed regarding the selection and maintenance of equipment, including improved containment of substances and recovery during servicing and at the end-of-life.

4. Important findings for sectors using ODSs and their alternatives

4.1 What are the most important findings for the refrigeration sector?

Refrigerants are by far the largest contributors to direct emissions of GHGs. In this report, the refrigeration sector is classified into the following subsectors: domestic refrigeration, commercial refrigeration, industrial refrigeration and food processing and cold storage and transport refrigeration. The sectors residential and commercial air conditioning and heating (SAC) and mobile air conditioning (MAC) are presented in separate sections (4.2 and 4.3) in this Technical Summary. Table TS-11 presents a detailed breakdown of banks and direct emissions of GHGs over all these sectors utilizing refrigerants.

The five general options to reduce direct GHG emissions for the refrigeration sector can be specified as follows:
- improved containment: leak-tight systems;
- recovery, recycling and the destruction of refrigerants during servicing and at the end-of-life of the equipment;
- application of reduced charge systems:
  - lower refrigerant charge per unit of cooling capacity;
  - reduced refrigeration capacity demand;
- use of alternative refrigerants with a reduced or negligible global-warming potential (e.g. hydrocarbons (HCs), carbon dioxide (CO_2), ammonia, etc.);
- not-in-kind technologies.

These principles equally apply for the SAC and MAC sectors.

4.1.1 Domestic refrigeration

Domestic refrigerators and freezers are used for food storage in dwelling units and in non-commercial areas such as offices throughout the world. More than 80 million units are produced annually with internal storage capacities ranging from 20 litres to more than 850 litres. With an estimated unit average lifespan of 20 years, this results in an installed inventory of approximately 1500 million units. As a result of the Montreal Protocol, manufacturers initiated the transition from CFC refrigerant applications during the early 1990s. This transition is complete in developed countries and has made significant progress in developing countries. However, the typical lifespan of domestic refrigerators results in units manufactured using CFC-12 refrigerant still comprising the majority of the installed base. This in turn significantly retards the rate of reduction in the demand for CFC-12 refrigerant in the servicing sector.

Isobutane (HC-600a) and HFC-134a are the major alternative refrigerants replacing CFC-12 in new domestic refrigeration equipment (see Table TS-12). Each of these has demonstrated mass production capability for safe, efficient, reliable and economic use. Similar product efficiencies result from the use of either refrigerant. Independent studies have concluded that application design parameters introduce more efficiency variation than is presented by the refrigerant choice. Comprehensive refrigerant selection criteria include safety, environmental, functional, cost and performance requirements. The choice of refrigerant can be strongly influenced by local regulatory and litigation environments. Each refrigerator typically contains 50–250 g of refrigerant enclosed in a factory-sealed hermetic system. A simplified summary of relative technical considerations for these two refrigerants is:

- HC-600a uses historically familiar mineral oil as the lubricant in the hermetic system. Manufacturing processes and designs must properly deal with the flammable nature of this refrigerant. Among these are the need for proper factory ventilation and appropriate electrical equipment, prevention of refrigerant leakage and access to electrical components, use of sealed or non-sparking electrical components when there is accessibility to leaking refrigerant and the use of proper brazing techniques or, preferably, avoidance of brazing operations on charged systems. Field service procedures must also properly accommodate the refrigerant flammability.
- HFC-134a uses moisture-sensitive polyolester oil as the lubricant in the hermetic system. Manufacturing processes and service procedures must take care to properly maintain low moisture levels. Long-term reliability requires a more careful avoidance of contaminants during production or servicing compared to either CFC-12 or HC-600a practices.

The use of the hydrocarbon blend propane (HC-290)/isobutane (HC-600a) allows the matching of CFC-12 volumetric capacity and avoids capital expense for retooling compressors. These blends introduce manufacturing complexities and require the use of charging techniques suitable for refrigerant blends having components with different boiling points. Application of these blends in Europe during the 1990s was an interim step towards the transition to HC-600a using retooled compressors. The safety considerations for hydrocarbon blends are consistent with those for HC-600a.

Table TS-11. Refrigerant bank and direct emissions of CFCs, HCFCs, HFCs and other substances (hydrocarbons, ammonia and carbon dioxide) in 2002, the 2015 business-as-usual scenario and the 2015 mitigation scenario, for the refrigeration sector, the residential and commercial air-conditioning and heating sector (‘stationary air conditioning’) and the mobile air-conditioning sector.

	Banks (kt)					Emissions (kt yr^{-1})					Emissions (MtCO$_2$-eq yr^{-1}) SAR/TAR[b]	Emissions (MtCO$_2$-eq yr^{-1}) This Report[c]
	CFCs	HCFCs	HFCs	Other	Total	CFCs	HCFCs	HFCs	Other	Total		
2002												
Refrigeration	330	461	180	108	1079	71	132	29	18	250	848	1060
- Domestic refrigeration	*107*	-	*50*	*3*	*160*	*8*	-	*0.5*	*0.04*	*9*	*69*	*91*
- Commercial refrigeration	*187*	*316*	*104*	-	*606*	*55*	*107*	*23*	-	*185*	*669*	*837*
- Industrial refrigeration[a]	*34*	*142*	*16*	*105*	*298*	*7*	*24*	*2*	*18*	*50*	*92*	*110*
- Transport refrigeration	*2*	*4*	*10*	-	*16*	*1*	*1*	*3*	-	*6*	*19*	*22*
Stationary Air Conditioning	84	1028	81	1	1194	13	96	6	0.2	115	222	271
Mobile Air Conditioning	149	20	249	-	418	60	8	66	-	134	583	749
Total 2002	**563**	**1509**	**509**	**109**	**2691**	**144**	**236**	**100**	**18**	**499**	**1653**	**2080**
2015 BAU												
Refrigeration	64	891	720	136	1811	13	321	115	21	471	919	1097
- Domestic refrigeration	*37*	-	*189*	*13*	*239*	*5*	-	*8*	*1*	*13*	*51*	*65*
- Commercial refrigeration	*6*	*762*	*425*	-	*1193*	*5*	*299*	*89*	-	*393*	*758*	*902*
- Industrial refrigeration(a)	*21*	*126*	*85*	*123*	*356*	*4*	*21*	*11*	*21*	*56*	*88*	*104*
- Transport refrigeration	*0.1*	*2.8*	*20.3*	-	*23.2*	*0.1*	*1.3*	*7.4*	-	*9*	*22*	*26*
Stationary Air Conditioning	27	878	951	2	1858	7	124	68	0	199	314	370
Mobile Air Conditioning	13	23	635	4	676	5	11	175	1	191	281	315
Total 2015-BAU	**104**	**1792**	**2306**	**143**	**4345**	**25**	**455**	**359**	**23**	**861**	**1514**	**1782**
2015 Mitigation												
Refrigeration	62	825	568	186	1641	8	202	52	15	278	508	607
- Domestic refrigeration	*35*	-	*105*	*60*	*200*	*3*		*3*	*1*	*6*	*27*	*35*
- Commercial refrigeration	*6*	*703*	*378*	-	*1087*	*3*	*188*	*40*	-	*230*	*414*	*494*
- Industrial refrigeration(a)	*21*	*120*	*65*	*126*	*331*	*3*	*13*	*5*	*14*	*36*	*53*	*63*
- Transport refrigeration	*0.1*	*2.8*	*20.3*	-	*23.2*	*0.0*	*0.9*	*4.3*	-	*5*	*13*	*15*
Stationary Air Conditioning	27	644	1018	2	1691	3	50	38	0	91	145	170
Mobile Air Conditioning	13	23	505	70	611	3	7	65	7	82	119	136
Total 2015 Mitigation	**102**	**1493**	**2090**	**259**	**3943**	**14**	**259**	**155**	**22**	**451**	**772**	**914**

[a] Including food processing/cold storage

[b] Greenhouse gas CO$_2$-equivalent (GWP-weighted) emissions, using direct GWPs, taken from IPCC (1996 and 2001) (SAR/TAR)

[c] Greenhouse gas CO$_2$-equivalent (GWP-weighted) emissions, using direct GWPs, taken from Chapter 2 in this report

Table TS-12. Domestic refrigeration, current status and abatement options.

Product Configuration		**Cold Wall**	**Open Evaporator Roll Bond**	**No-Frost**
Cooling capacity	From	60 W	60 W	120 W
	To	140 W	140 W	250 W
Refrigerant charge (HFC)	From	40 g	40 g	120 g
	To	170 g	170 g	180 g
Approximate percentage of sector refrigerant bank (160 kt) in configuration		20 units @ 100 g average 18% of 160 kt	15 units @ 100 g average 14% of 160 kt	50 units @ 150 g average 68% of 160 kt
Approximate percentage of sector refrigerant emissions (8950 tonnes) in subsector		18% of 8950 tonnes	14% of 8950 tonnes	68% of 8950 tonnes
Predominant technology		HC-600a	HFC-134a	HFC-134a
Other commercialized technologies		HFC-134a, CFC-12	HC-600a, CFC-12	HC-600a, CFC-12
Low GWP technologies with fair or better than fair potential for replacement of HCFC/HFC in the markets		R-600a	HC-600a	HC-600a
Status of alternatives		Fully developed and in production	Fully developed and in production	Fully developed and in production
HC-600a Mfg. Cost Premium		No Premium	3–5 US$	8–30 US$
Capital Investment		0	45–75 million US$	400–1500 million US$
Emission reduction		1432 tonnes	1253 tonnes	6086 tonnes

Alternative refrigeration technologies such as the Stirling cycle, absorption cycle and thermoelectric, thermionic and thermoacoustic systems continue to be pursued for special applications or situations with primary drivers different from conventional domestic refrigerators. These technology options are not expected to significantly alter the position of vapour compression technology as the technology of choice for domestic refrigeration in the foreseeable future.

Vapour compression technology is established and readily available worldwide. Current technology designs, based on HC-600a or HFC-134a, typically use less than one-half the electrical energy required by the units they replace. This reliable performance is provided without resorting to higher cost or more complex designs. Continued incremental improvements in unit performance and/or energy efficiency are anticipated. Government regulations and voluntary agreements on energy efficiency and labelling programmes have demonstrated their effectiveness in driving improved efficiency product offerings in several countries.

Good design, manufacturing and service practices will minimize refrigerant emissions during refrigerator production and use phases; however, special attention must be given to the retirement of the large number of units containing CFC-12. With a typical 20-year lifespan, refrigerator end-of-life retirement and disposal occurs at a frequency of about 5% of the installed base each year. This means approximately 75 million refrigerators containing 100 g per unit, or a total of 7500 tonnes of refrigerant, are disposed of annually. For at least another 10 years, this refrigerant will predominantly be CFC-12. The small refrigerant charge per unit detracts from the economic justification for refrigerant recovery. Regulating agencies around the world have provided incentives or non-compliance penalties to promote recovery of this ODS.

The current (2002 data) annualized HFC-134a emissions rate from domestic refrigerators is 1.0% during product usage. HFC emissions for domestic refrigeration are estimated to be 480 tonnes in 2002, increasing to 7800 tonnes by 2015 in a BAU scenario. In the mitigation-scenario, emissions in 2015 are 2800 tonnes due to improved refrigerant containment and recovery. Table TS-12 summarizes emission abatement opportunities with increased application of HC-600a refrigerant. Similarly, the manufacturing cost premiums and capital investments and development costs required for implementation are tabulated for the three most common refrigerator configurations.

4.1.2 Commercial refrigeration

Commercial refrigeration comprises three main types of equipment: stand-alone equipment, condensing units and full supermarket systems. A wide variety of refrigeration systems fall within the subsector of commercial refrigeration, from ice-cream freezers, with a cooling capacity of about 200 W and not varying greatly from domestic freezers, up to machinery rooms containing multiple compressor racks that consume several hundreds of kilowatts. The most commonly used refrigerants in this subsector are HCFC-22, R-404A and HFC-134a.

In 2002, all refrigerant types banked in commercial refrigeration, predominantly equipment containing CFCs, HCFCs and HFCs, represented 605 kt of a total of 2690 kt for all refrigerating and air conditioning (AC) systems and all refrigerant types; this represents 22% of the total refrigeration and AC bank.

On a global basis, commercial refrigeration is the refrigeration subsector with the largest refrigerant emissions, calculated as CO_2-equivalents, representing 40% of the total refrigerant emissions (in refrigeration, SAC and MAC). The emission levels, including fugitive emissions, ruptures and emissions during servicing and at end-of-life, are generally very high, especially for supermarkets and hypermarkets. The larger the charge, the larger the average emission rate, which results from very long pipes, large numbers of fittings and valves and very high emissions when ruptures occur.

Refrigerant leakage rates derived with a bottom-up approach suggest a global annual emissions rate of 30% of banked system charge. Refrigerant emissions typically represent 60% of the total emissions of GHGs resulting from the system operation, with the remainder being indirect emissions caused by power production. These percentages indicate how important emission reductions from this sector are.

Annual refrigerant leakage rate data from over 1700 full supermarket systems in the USA and Europe are in the range of 3–22% of system charge, with an average of 18%. It may be concluded that if the emission estimate of 30% on a global basis is correct, the values of 3–22% must represent selected company data from countries with a strong emphasis on emission reductions.

Projections of future halocarbon refrigerant emissions according to different scenarios are given in Table TS-11. The high economic growth rates of some of the developing countries will have a very significant impact on the growth of the refrigerant bank and emissions.

Significant total emission reductions, that is improved LCCP, can be achieved by using refrigerants like HFCs, hydrocarbons, ammonia or CO_2, by employing charge reduction and more efficient containment and by overall improved energy efficiency through new system designs. This is summarized in Table TS-13. Safety issues have to be taken into account if toxic or flammable refrigerants are used; these depend on national and, occasionally, on local regulations, which may limit the degree to which some of these refrigerants can be applied.

In full supermarket systems, up to 60% lower LCCP values than in centralized direct systems of traditional design can be obtained by applying direct systems using alternative refrigerants, better containment, distributed systems, indirect systems or cascade systems.

Published results show that alternative systems have a 0–35% higher initial cost and a 0–20% higher energy usage than current systems.

Refrigerant emissions abatement cost is in the range of 20–280 US\$/tCO_2-eq[19,20]. Development work on new systems is continuing in order to reduce cost and energy usage in these systems, which will further reduce abatement costs. Taking into consideration possible increases in energy efficiency may also result in negative abatement costs (savings).

For small commercial units, namely stand-alone equipment and condensing units (vending machines, ice-cream freezers, walk-in coolers, etc.), global companies have begun employing low- or zero-GWP alternatives to HFCs (hydrocarbons and CO_2) and alternative technologies. Both of these options promise reduced direct and comparable or lower indirect emissions.

4.1.3 Food processing, cold storage and industrial refrigeration

Food processing and cold storage is one of the important applications of refrigeration; the preservation and distribution of food while keeping nutrients intact. This application is very significant in size and economic importance in all countries, including developing ones. The application includes both cold storage (at temperatures from –1°C to 10°C), freezing (–30°C to –35°C) and the long-term storage of frozen products (–20°C to –30°C). The amount of chilled food is about 10 to 12 times greater than the amount of frozen products.

---

[19] Costs in this report are given in US dollars in 2002 unless otherwise stated.

[20] The presented cost data are for direct emission reductions only. The taking into account of energy efficiency improvements may result in even net negative specific costs (savings).

Table TS-13. Sector summary for commercial refrigeration – current status and abatement options.

Subsector		**Stand-alone Equipment**	**Condensing Units**	**Full supermarket system**			
				Direct Centralized	**Indirect Centralized**	**Distributed**	**Hybrids**
Cooling capacity	From	0.2 kW	2 kW	20 kW			
	To	3 kW	30 kW	>1000 kW			
Refrigerant charge	From	0.5 kg	1 kg	100 kg	20	*	*
	To	~2 kg	15 kg	2000 kg	500 kg	*	*
Approximate percentage of sector refrigerant bank in subsector		11% of 606 kt	46% of 606 kt	43% of 606 kt			
Approximate percentage of sector refrigerant emissions in subsector		3% of 185 kt	50% of 185 kt	47% of 185 kt			
2002 Refrigerant bank, percentage by weight		CFCs 33%, HCFCs 53%, HFCs 14%					
Typical annual average charge emission rate		30%					

Subsector	**Stand-alone Equipment**	**Condensing Units**	**Full supermarket system**			
			Direct Centralized	**Indirect Centralized**	**Distributed**	**Hybrids**
Technologies with reduced LCCP	**Improved HFC** SDNA	**Improved HFC** SDNA	**Improved HFC** EmR 30% ChEU 0% ChCst 0 ±10%	**Ammonia** EmR 100% ChEU 0–20% ChCst 20–30%	**HFC** EmR 75% ChEU 0–10% ChCst 0–10%	**Cascade-HFC/CO_2** EmR 50–90% ChEU 0%
	HC SDNA	**R-410A** SDNA	**CO_2 (all-CO_2)** EmR 100% ChEU 0 ±10% ChCst 0±10%	**HC** EmR 100% ChEU 0–20 % ChCst 20–30%	**Economized-HFC-404A** SDNA	**Cascade-Ammonia/CO_2** SDNA
	CO_2 SDNA	**HC** SDNA		**HFC** EmR 50–90% ChEU 0–20% ChCst 10–25%	**Economized-HFC-410A** SDNA	**Cascade-HC/CO_2** SDNA
		CO_2 SDNA			**CO_2** SDNA	
LCCP reduction potential (world avg. emission factor for power production)	SDNA		35–60%			
Abatement cost estimates (10-yr lifetime, 10% interest rate)	SDNA		20–280 US$ per tonne CO_2 mitigated			

Notes:
* Alternatives in these categories have been commercialized, but since the current number of systems are limited, they are only referenced as options below
EmR (%): Direct Emission Reduction (compared with installed systems)
ChEU (%): Change in Energy Usage (+/–) (compared with state of the art)
ChCst (%): Change in Cost (+/–) (compared with state of the art)
SDNA: Sufficient data on emission reduction, energy usage and change in cost not available from literature

The majority of refrigerating systems for food processing and cold storage are based on reciprocating and screw compressors. Ammonia, HCFC-22, R-502 and CFC-12 are the historically used refrigerants. HFC refrigerants are currently being used in place of CFC-12, R-502 and HCFC-22 in certain regions. The preferred HFCs are HFC-134a and HFC blends with a small temperature glide such as R-404A, R-507A and R-410A. Ammonia/CO_2 cascade systems are also being used, as are hydrocarbons as primary refrigerants in indirect systems.

Limited data are available on TEWI/LCCP for this category. A recent study of system performance and LCCP calculations for an 11-kW refrigeration system operating with R-404A, R-410A and HC-290 showed negligible differences in LCCP, based on the assumptions used in the calculations.

Additional information on refrigerant leakage and emissions reduction options for the total sector of food processing, cold storage and industrial refrigeration is included at the end of the following section.

Industrial refrigeration includes a wide range of cooling and freezing applications, such as those in the chemical, oil and gas industries, industrial and recreational ice making and air liquefaction. Most systems are vapour compression cycles, with evaporator temperatures ranging from 15°C down to –70°C. Cryogenic applications operate at even lower temperatures. The capacity of the units varies from 25 kW to 30 MW, with systems often custom-made and erected on-site. The refrigerants used are preferably single component or azeotropes because many of the systems use flooded evaporators to achieve high efficiency. Some designs use indirect systems with heat transfer fluids to reduce refrigerant charge size and/or to minimize the risk of direct contact with the refrigerant.

These refrigeration systems are normally located in industrial areas with limited public access. Ammonia is the predominant and increasingly used refrigerant, with the second most common refrigerant in terms of volume use being HCFC-22, although the use of HCFC-22 in new systems is forbidden by European regulations since January 2001 for all types of refrigerating equipment. The smaller volume CFC refrigerants CFC-12 and R-502 are being replaced by HFC-134a and by R-404A, R-507A and R-410A. CFC-13 and R-503 are being replaced by HFC-23 and by R-508A or R-508B. HCFC-22 is being replaced by R-410A, as the energy efficiency of R-410A systems can be slightly higher than that of HCFC-22, and R-410A is similar to ammonia with respect to evaporation temperatures down to –40°C. Hydrocarbon refrigerants historically have been used in large refrigeration plants within the oil and gas industry.

CO_2 is beginning to find application in this subsector as a low-temperature refrigerant and in cascade systems, with ammonia in the high stage and CO_2 in the low stage. The energy efficiency of CO_2 systems can be similar to that of HCFC-22, ammonia and R-410A in the evaporator range of –40°C to –50°C. CO_2 is also being used as an indirect system heat transfer fluid.

Annual refrigerant leakage rates of industrial refrigeration systems have been estimated to be in the range of 7–10%, while those for the combined sector of food processing, cold storage and industrial refrigeration were reported to be 17% of the total systems refrigerant bank in 2002. The refrigerant bank consisted of 35% ammonia and 43% HCFC-22 by weight, with the remainder being CFCs, HFCs and hydrocarbons. The 2002 distribution of the major refrigerants and emissions in this total sector are shown in Table TS-14.

Emission reduction options are to use refrigerants with lower GWP, to improve design of equipment and operations resulting in a reduced system refrigerant charge, to improve refrigerant containment and recovery and to improve energy efficiency through new system designs. LCCP calculations should be used in optimizing refrigerant choice and system design for the lowest environmental impact. Industrial refrigeration refrigerant emissions abatement cost was determined to be in the range of 27–37 US\$/tCO_2-eq (8% yr^{-1} discount rate).

4.1.4 Transport refrigeration

The transport refrigeration subsector consists of refrigeration systems for transporting chilled or frozen goods by road, rail, air and sea. Several types of refrigeration configurations are used, such as shipboard systems, containers with individual refrigeration units which can be transported by sea, rail or road and refrigerated trucks and railcars. The transport subsector also covers the use of refrigeration in fishing

Table TS-14. Food processing, cold storage and industrial refrigeration (2002).

	CFCs (CFC-12 and R-502)	**HCFC-22**	**NH_3**	**HFCs** (HFC-134a, R-404A, R-507A, R-410A)
Cooling Capacity	25 kW–1000 kW	25 kW–30 MW	25 kW–30 MW	25 kW–1000 kW
Emissions, t yr^{-1}	9500	23,500	17,700	1900
Refrigerant in bank, tonnes	48,500	127,500	105,300	16,200
Emissions % yr^{-1}	14%	18%	17%	12%

Table TS-15. Transport refrigeration, characteristics and alternatives.

Subsector		Sea Transport & Fishing	Road Transport	Rail Transport	Container Transport
Cooling capacity	From	5 kW	2 kW	10 kW	Approx. 5 kW
	To	1400 kW	30 kW	30 kW	
Refrigerant charge	From	1 kg	1 kg	10 kg	Approx. 5 kg
	To	Several tonnes	20 kg	20 kg	
Approximate percentage of sector refrigerant bank in subsector		52% of 15,900 tonnes	27% of 15,900 tonnes	5% of 15,900 tonnes	16% of 15,900 tonnes
Approximate percentage of sector refrigerant emissions in subsector		46% of 6000 tonnes	30% of 6000 tonnes	6% of 6000 tonnes	18% of 6000 tonnes
Predominant technology		HCFC-22	HFC-134a, HFC-404A, HFC-410A	HFC-134a, HFC-404A, HFC-410A	HFC-404A
Other commercialized technologies		Various HFCs, ammonia, ammonia, CO_2 /ammonia for low temperatures; hydrocarbon systems for gas tankers; sorption systems for part of the cooling load	Hydrocarbons, liquid or solid CO_2, ice slurry, eutectic plates	Solid CO_2	HFC-134a, HCFC-22
Low GWP technologies with fair or better than fair potential for replacement of HCFC/HFC in the markets		Ammonia, CO_2 /ammonia for low temperatures	Hydrocarbons, CO_2 compression systems; for short hauls a combination of stationary hydrocarbon or ammonia with liquid CO_2, ice slurry or eutectic plates	Hydrocarbons, CO_2 compression systems; for specific transports (certain fruits) a combination of stationary hydrocarbon or ammonia with liquid CO_2, ice slurry or eutectic plates	CO_2 compression system
Status of alternatives		Fully developed. Some cost issues related to additional safety for ammonia plants on ships. Hydrocarbon practical mainly for ships which are built according to explosion-proof standards (e.g. gas carriers)	Hydrocarbon mini-series successfully field tested, lack of demand and additional requirements on utilization (driver training, parking). Liquid CO_2 systems commercialized. CO_2 compression tested in prototypes, but open-drive compressor needed for most systems in combination with leakage is an issue	Solid CO_2 is standard use, but not very energy efficient, difficult to handle and high infrastructure requirements, therefore presently being phased out. Increasingly use of systems designed for trailer use with optimization for rail requirements (shock resistance)	Under development – prototype testing; might be available in the near future if demanded

vessels where the refrigeration systems are used for both food processing and storage.

Technical requirements for transport refrigeration units are more stringent than for many other applications of refrigeration. The equipment has to operate in a wide range of ambient temperatures and under extremely variable weather conditions (solar radiation, rain, etc). The transport equipment must be able to carry a highly diverse range of cargoes with differing temperature requirements and must be robust and reliable in the often severe transport environment. Despite the robust and sturdy design of transport refrigeration units, leaks within the refrigeration system can occur as a result of vibrations, sudden shocks, collisions with other objects and salt-water corrosion. Ensuring the safe operation with all working fluids is essential if – for example, in the case of ships – there are no easy options for evacuation in the case of refrigerant leakage. Safety must be inherent through the choice of fluids or ensured through a number of technical measures. There is also a need for continuity with respect to equipment maintenance, as the transport equipment can require servicing in many locations around the world.

Refrigeration systems are typically using CFC-12, R-502, HCFC-22, HFC-134a, R-404A, R-507A, R-410A and R-407C. Lower GWP alternatives, such as ammonia, hydrocarbons and ammonia/CO_2, have been commercialized in some vapour compression applications. Ice and liquid or solid CO_2 are used in some sectors of transport refrigeration such as road, rail and air. An overview of the different applications currently used as well as the state of development of alternatives can be found in Table TS-15. The refrigerant bank is presently estimated to be 3300 tonnes of CFCs, 3200 tonnes of HCFC-22 and 9500 tonnes of HFCs and HFC mixtures; the total bank is expected to increase from 16,000 tonnes at the present time to 23,200 tonnes in 2015 (BAU scenario). The expectation is that present-day combined refrigerant emissions of 6000 tonnes annually will increase to 8700 tonnes annually by 2015 for a BAU scenario or will be 5250 tonnes annually following significantly increased efforts in refrigerant recovery and recycling and better containment such as the use of hermetically sealed compressors. These latter options would significantly lower CO_2-equivalent emissions, as would the replacement of fluorocarbons with lower GWP alternatives.

There are lower-GWP refrigerant replacement options available for all transport refrigeration applications where CFCs, HCFCs or HFCs are presently being used; see Table TS-15. In several cases, these options might increase the costs of the refrigeration system due to equipment- and safety-related costs. It must be remembered that for the owners of transport equipment, and in the absence of external incentives, the initial cost of the transport system and refrigeration plant is far more important than the running costs of the installation.

Due to refrigerant leakage rates of 25–35%, the change from an HFC such as R-404A to a lower GWP alternative will usually lead to a reduction of the TEWI, if the energy consumption is not substantially higher than in today's systems. In several applications, the reduction of TEWI could be very significant.

There are many opportunities for reducing the energy consumption of transport refrigeration systems, including improved insulation to reduce cooling losses and load, compressor frequency control for partial load conditions, water-cooled condensers for shipboard systems and preventive maintenance to reduce heat exchanger fouling.

4.2 What are the most important findings for residential and commercial air conditioning and heating?

The applications, equipment and products that are included in the sector of residential and commercial air conditioning and heating can be classified into three groups: stationary air conditioners (including both equipment that cools air and heat pumps that directly heat air), chillers and water-heating heat pumps.

Stationary air conditioners generally fall into six distinct categories: (1) window-mounted and through-the-wall; (2) non-ducted split residential and commercial; (3) non-ducted single-package; (4) non-ducted water-source; (5) ducted residential split and single packaged; (6) ducted commercial split and packaged. Water chillers coupled with air handling and distribution systems commonly provide comfort air conditioning in large commercial buildings. Water-heating heat pumps are manufactured using various heat sources: air, water from ponds and rivers and the ground.

Which refrigerants were used in the past?

- HCFC-22 in unitary air conditioners;
- HCFC-22 and R-502 in water-heating heat pumps;
- CFC-11, CFC-12, HCFC-22 and R-500 in centrifugal water chillers;
- HCFC-22 and CFC-12 (to a much lower extent) in positive displacement water chillers.

Stationary air conditioners: The vast majority of stationary air conditioners (and air-heating heat pumps) use the vapour-compression cycle technology with HCFC-22 refrigerant. Nearly all air-cooled air conditioners manufactured prior to 2000 use this refrigerant as their working fluid.

Water chillers: Chillers employing screw, scroll and reciprocating compressors generally employ HCFC-22. Some of the smaller reciprocating chillers (under 100 kW) were offered with CFC-12 as the refrigerant. Centrifugal chillers are manufactured in the United States, Asia and Europe. Prior to 1993, these chillers were offered with CFC-11, CFC-12, R-500 and HCFC-22 as refrigerants.

Water-heating heat pumps: In the past, the most common refrigerants for vapour compression heat pumps have been R-502 and HCFC-22.

What are current practices?

Stationary air conditioners: A rough estimate would indicate that globally more than 90% of the air-cooled air conditioner (and heat pump) units currently being produced still use HCFC-22 as the refrigerant. This refrigerant is beginning to be phased out in some countries ahead of the schedule dictated by the Montreal Protocol. The refrigerant options being used to replace HCFC-22 are the same for all of the stationary air conditioner categories: HFC-134a, HFC blends and hydrocarbons. CO_2 is also being considered for this application. At present, HFC blends are being used in the vast majority of non-ODS systems, with hydrocarbons being used in a small percentage of low charge systems.

Water chillers: HFCs and HFC blends (particularly R-407C and R-410A) are beginning to replace HCFC-22 unit sales in new positive displacement chillers. Larger water-cooled screw chillers (e.g. above 350 kW) have been developed to use HFC-134a rather than HCFC-22. Ammonia is used in some chillers in Europe, and a few small chillers using hydrocarbon refrigerants are also produced there each year. HCFC-123 and HFC-134a have replaced CFC-11 and CFC-12 in centrifugal chillers produced since 1993.

Water-heating heat pumps: In developed countries, HCFC-22 is still the most commonly used refrigerant, but HFC alternatives are being introduced. In developing countries, CFC-12 is also still used to a limited extent. Alternatives to HFCs in small residential and commercial water-heating systems include hydrocarbons and CO_2. Hydrocarbons are being used in Europe and CO_2 is being used in Europe and Asia.

What are possible future trends?

Options to reduce GHG emissions in residential and commercial air conditioning and heating equipment involve containment in CFC/HCFC/HFC vapour-compression systems that are applicable worldwide and for all equipment, and the use of non-CFC/HCFC/HFC systems. This latter option is not applicable in all instances due to economic, safety and energy efficiency considerations.

Containment can be achieved through the improved design, installation and maintenance of systems to reduce leakage and minimize refrigerant charge quantities in the systems, and the recovery, recycling and reclaiming of refrigerant during servicing and at equipment disposal. In order to minimize installation, service and disposal emissions, a trained labour force using special equipment is required. The baseline emissions and the emissions in a mitigation scenario for 2015 are presented in Table TS-11.

What are alternative low GWP-refrigerants?

Depending on the application, alternative refrigerants to HFCs in residential and commercial air conditioning and heating equipment can include hydrocarbons, ammonia, water and CO_2.

Stationary air conditioners: The use of hydrocarbons in air-cooled air conditioning products having refrigerant charge levels greater than 1 kg has been the focus of considerable risk analysis and safety standards development activities (e.g. European Standard EN 378). The most significant issue that will confront a manufacturer when considering applying hydrocarbon refrigerants is the determination of an acceptable level of risk and the associated liability.

CO_2 offers a number of desirable properties as a refrigerant: availability, low toxicity, low direct GWP and low cost. CO_2 systems are also likely to be smaller than those using common refrigerants. These benefits are offset by the fact that the use of CO_2 in air conditioning applications requires high operating pressures and results in low operating efficiencies, thereby contributing to increased indirect CO_2 emissions through higher energy consumption. Actual system tests of non-optimized air conditioning systems have demonstrated COPs[21] up to 2.25 at air inlet temperatures of 35°C compared to COPs up to 4.0 for typical HCFC-22 equipment.

Water chillers: Positive displacement chillers using ammonia as the refrigerant are available in the capacity range from 100 to 2000 kW with a few being larger. Recommended practice guidelines limit the use of large ammonia systems in public buildings to situations in which the ammonia is confined to the machine room where alarms, venting devices and scrubbers can enhance safety. Guidelines are available for the safe design and application of ammonia systems. Modern, compact factory-built units contain the ammonia much more effectively than old ammonia plants.

Hydrocarbon refrigerants have a long history of application in industrial chillers in petrochemical plants. Before 1997, they were not used in comfort air conditioning chiller applications due to reservations about systems safety. European manufacturers now offer a range of positive displacement hydrocarbon chillers. Unit sales of hydrocarbon chillers amount to about 100 to 150 annually, primarily in northern Europe. This is a small number compared with the installed base of more than 77,000 HCFC and HFC chillers in Europe. Typical safety measures include proper placement and/or gas-tight enclosure of the chiller, application of the low-charge system design, fail-safe ventilation systems, and gas detector alarm-activating systems. Efficiency is similar to that of equivalent HCFC-22 products. The cost of hydrocarbon chillers is higher than that of HCFC or HFC equivalents.

CO_2 is being investigated for a wide range of potential applications. However, CO_2 does not match cycle energy efficiencies of fluorocarbon refrigerants for typical water chilling applications and, consequently, there is no environmental incentive to use CO_2 in chillers in place of HFCs. There has been no commercial application of CO_2 in chillers to date.

---

[21] COP stands for Coefficient of Performance, a measure of the energy efficiency of a refrigerating system.

Water is an attractive alternative because it is non-toxic and non-flammable. However, it is a very low-pressure refrigerant. The low pressures and very high volumetric flow rates required in water vapour-compression systems necessitate compressor designs that are uncommon in the air conditioning field. The few applications that exist use water as a refrigerant to chill water or to produce ice slurries by direct evaporation from a pool of water. These systems currently carry a cost premium of more than 50% above conventional systems. The higher costs are inherent and are associated with the large physical size of water vapour chillers and the complexity of their compressor technology.

Water-heating heat pumps: Some European manufacturers are using propane (HC-290) or propylene (HC-1270) as refrigerants in small low-charge residential and commercial water-heating heat pumps. The hydrocarbon circuit is typically located outdoors or in a ventilated indoor space and uses ambient air, earth or ground water sources.

In water-heating applications, propane will yield the same or slightly higher energy efficiency as HCFC-22. When designing new heat pump systems with propane or other flammable refrigerants, adequate safety precautions must be taken to ensure safe operation and maintenance. Several standards that regulate the use of hydrocarbons in heat pumps exist or are being developed in Europe, Australia and New Zealand. An example of a standard under development is an update of European Standard EN 378.

The transcritical CO_2 cycle exhibits a significant temperature glide on the high temperature side. Such a glide can be of benefit in a counter-flow heat exchanger. Heat pumps using CO_2 as the refrigerant can generate water temperatures up to 90°C and have been developed in Japan for home use. A typical heating capacity is 4.5 kW.

Ammonia has been applied in medium-size and large-capacity heat pumps, mainly in Scandinavia, Germany, Switzerland and the Netherlands. System safety requirements for ammonia heat pumps are similar to those for ammonia chillers.

What are alternative not-in-kind technologies?

A number of other non-traditional technologies have been examined for their potential to reduce the consumption and emission of HFCs. These include desiccant systems, Stirling cycle systems, thermoelectrics, thermoacoustics and magnetic refrigeration. With the exception of the Stirling cycle and desiccants, these all suffer such large efficiency penalties that the consequent indirect effects would overwhelm any direct emission reduction benefit. Despite receiving research interest, the Stirling cycle has remained limited to niche applications and has never been commercialized for air conditioning. In high latent load applications, desiccant systems have been applied to supplement the latent performance of traditional mechanical air conditioning.

What is the overall reduction potential?

Direct GHG emissions of residential and commercial air conditioning and heating equipment can be reduced by about 200 $MtCO_2$-eq yr^{-1} relative to the BAU scenario (2015). Specific costs range from –3 to 170 US\$/tCO_2-eq. Improved system energy efficiencies can significantly reduce indirect GHG emissions, leading in some cases to overall savings of 75 US\$/tCO_2-eq. Opportunities to reduce direct GHG (i.e. refrigerant) emissions can be found in (1) a more efficient recovery of refrigerant at end-of-life (in the mitigation scenario, assumed to be up to 50% and 80% for developing and developed countries, respectively); (2) charge reduction (up to 20%); (3) better containment; (4) the use of non-fluorocarbon refrigerants in suitable applications.

4.3 What are the most important findings for mobile air conditioning?

What are past and current trends in MAC?

MAC systems have been mass produced in the USA since the early 1960s and in Japan since the 1970s. The significant increase in the numbers of air-conditioned cars in Europe and also in developing countries began later, around 1995.

As indicated in Table TS-16, the global CFC-12 fleet has decreased from approximately 212 million vehicles in 1990 to 119 million vehicles in 2003, while the HFC-134a fleet has increased from fewer than 1 million in 1992 up to 338 million in 2003.

On the basis of a BAU scenario, and including high economic growth of rapidly-developing countries, Figure TS-11 shows a projected increase in the air-conditioned fleet that reaches approximately 965 million air-conditioned vehicles by 2015.

What are current emissions and projections?

Emissions from vehicles continuing to use MAC systems with CFC-12 are about 531 g yr^{-1} $vehicle^{-1}$ when all types of emissions are included (fugitive emissions represent 220 g yr^{-1} $vehicle^{-1}$). Recovery and recycling are performed for CFC-12 in end-of-life of vehicles in some countries, but the CFC-12 will still eventually be released into the atmosphere following these practices unless it is destroyed. The annual emissions (2002) from the global fleet of air-conditioned CFC-12-based vehicles are about 514 $MtCO_2$-eq yr^{-1} (fugitive emissions represent 213 $MtCO_2$-eq yr^{-1}). Projections suggest

Table TS-16. MAC fleet evolution and refrigerant choice from 1990 to 2003.

Year	AC vehicle fleet (million) CFC-12	HFC-134a
1990	212	-
1991	220	-
1992	229	0.7
1993	229	10
1994	222	27
1995	215	49
1996	206	74
1997	197	100
1998	186	128
1999	175	161
2000	163	198
2001	149	238
2002	134	285
2003	119	338

that the effect of the MAC subsector on radiative forcing of the climate system will be dominated by emissions of CFC-12 through to 2006 at the earliest.

The direct emissions from the global fleet of HFC-134a-based MAC systems are estimated to be about 220 g yr^{-1} $vehicle^{-1}$ including fugitive emissions that account for 130 g yr^{-1} $vehicle^{-1}$ or, when expressed as CO_2-equivalents, about 96 $MtCO_2$-eq yr^{-1} including fugitive emissions that account for 56 $MtCO_2$-eq yr^{-1}. Current 'do-it-yourself' kits for recharging air conditioners that use disposable cans of fluids lead to at least a twofold increase in emissions to the atmosphere compared with professional servicing that uses more efficient fluid-delivery components.

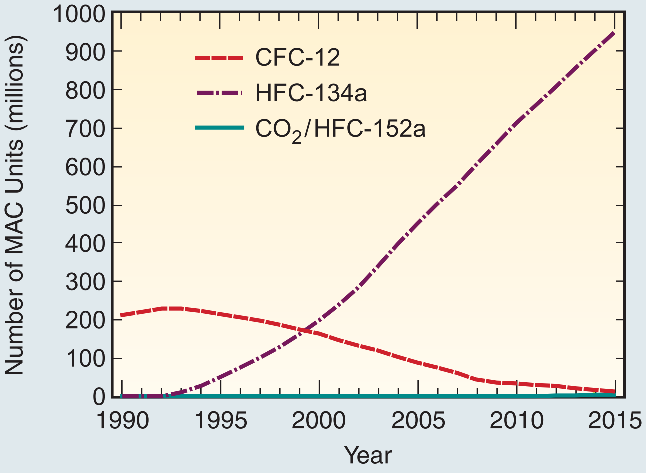


Figure TS-11. MAC fleet evolution from 1990 to 2015 in the BAU scenario.

Table TS-11 emphasizes the rapid change in refrigerant choice that has resulted from implementation of the Montreal Protocol.

What are the indirect energy-related CO_2 emissions related to MAC operation?

The operation of MAC systems worldwide leads to a substantial indirect effect through increased fuel use and associated CO_2 emissions. Current fuel consumption tests and standards in the motor vehicle industry do not explicitly evaluate this effect, which varies by climate zone. Depending on climate conditions, it is estimated that MAC systems represent 2.5–7.5% additional fuel consumption, or about 126 kg (Tokyo) to 369 (Phoenix) kg of CO_2 yr^{-1} $vehicle^{-1}$. With the total number of air-conditioned vehicles estimated to be 457 million (in 2003), the indirect effect corresponds to as much as 114 $MtCO_2$-eq yr^{-1} (when averaged across the global fleet and assuming an average value of 250 kg CO_2 yr^{-1} $vehicle^{-1}$) relative to 750 $MtCO_2$-eq yr^{-1} of direct emissions.

What are possible future trends in MAC?

The following options exist for reducing GHG emissions: (1) enhance the current HFC-134a systems; (2) move to lower GWP refrigerants, either HFC-152a or CO_2. Hydrocarbons, even if they are low GWP refrigerants and efficient when properly used, are not seen as suitable options by car makers and suppliers due to safety concerns.

'Improved' HFC-134a systems are being introduced progressively onto the market, at an additional cost varying from 24–36 US$ per system. These employ tighter hoses, compressors and service valves, all of which reduce leakage. Recent studies suggest that improved HFC-134a systems and improved servicing could result in emissions of about 70 g yr^{-1} $vehicle^{-1}$, which is about 60% lower than those from current HFC-134a systems. Improvements in recovery practices and service training could further reduce emissions. Significant energy savings are related to the use of variable volume compressors with an external control, which are also being progressively introduced in the market. Additional savings are related to a MAC system design that integrates energy efficiency constraints.

Several recent studies suggest that improvements in energy efficiency, through measures such as on/off controls instead of standard continuous operation, insulation of doors and roofs and so forth, could reduce these emissions by about 30–40%, which represents 30–40 $MtCO_2$-eq yr^{-1}.

Table TS-17. Comparison of MAC options.

	HFC-134a (reference)	Improved HFC-134a	CFC-12 (old type) development)	CO_2 (under development)	HFC-152a (direct system, under devolpment)
Substance characteristics					
Radiative efficiency (W m^{-2} ppb^{-1})	0.16	0.16	0.32	See Ch. 2	0.09
Atmospheric lifetime (yr)	14	14	100	See Ch. 2	1.4
Direct GWP (100-yr time horizon)					
- This report	1410	1410	10,720	1	122
- UNFCCC[a]	1300	1300	8100	1	140
Technical data					
Stage of development	Commercial	Near commercial	Commercial	Demonstration	Demonstration
System lifetime	12–16	12–16	12–16	12–16	12–16
Cooling capacity (kW)	6	5	6	6	6
Charge (kg/system)					
- range	0.7–0.9	0.6–0.75	1–1.2	0.5–0.7	0.45–0.55
- relative figures (%)	100	80	125	70	70
# Charges over lifetime	2–3	1–2	4	2–4	1–2
Coefficient of Performance (COP)	0.9–1.6	1.2–2.5	0.9–1.2	0.9–2.0	1.2–2.0
Energy consumption (relative figures)	100	80	130	70	70
Emissions per functional unit					
Direct emissions					
- in % of charge yr^{-1}	15	7	20	15	7
- in kg CO_2-eq yr^{-1}	166	64	1782	0.09	4.9
- relative figures (%)	100	40	1043	0.05	2.9
Indirect CO_2-emissions (kg CO_2 yr^{-1})					
- Sevilla	184	147	239	129	129
- Tokyo	126	101	163	88	88
- Phoenix	369	295	480	258	258
End-of-life emissions recovery efficiency[b]	0	50	0	0	50
TEWI (kg CO_2-eq 14 years)					
- Sevilla	4900	2954	28,294	1807	1875
- Tokyo	4088	2310	27,230	1233	1301
- Phoenix	7490	5026	31,668	3613	3681
(without recovery)[b]					
Costs per functional unit					
Investment costs (US$)	215	24–36	n.a.	48–180	48

Notes:

[a] The GWP values used for the calculations are the UNFCCC GWPs.

[b] Due to large uncertainties in the effectiveness of recovery, the TEWI calculations have not taken recovery into account and so the average direct emission per year for ‘improved HFC-134a systems’ is 100 g yr^{-1}.

MAC systems using CO_2 have been successfully demonstrated in passenger vehicles and commercial buses. CO_2 has a GWP that is 1300-fold smaller than HFC-134a, thereby limiting the direct effects per charge. However, CO_2 systems operate at pressures about eightfold higher than those of CFC-12 and HFC-134a (discharge pressures in the order of 12 MPa), and since leak flow rates are related to the square of the pressure, CO_2 systems imply a much more difficult containment. To date, CO_2 systems have shown an energy efficiency comparable to or better than improved HFC-134a systems in cooler ambient climates, but they are likely to be less efficient in warmer climates. Nevertheless, as indicated in Table TS-17, due to its nearly negligible direct effect, the TEWI of CO_2 systems is significantly better than that of improved HFC-134a systems. Barriers to commercialization include the resolution of additional costs and safety issues associated with the release of CO_2 within the passenger cabin and maintenance issues as well as the conversion cost of the service system.

HFC-152a has also been successfully demonstrated in MAC systems. While HFC-152a systems can use the same components as HFC-134a systems, the former require an added safety system because HFC-152a is flammable while HFC-134a is non-flammable. Direct emissions (in CO_2-equivalents) are very low (92% reduction, referred to as the HFC-134a baseline). HFC-152a systems have so far shown an energy efficiency comparable with or better than improved HFC-134a systems, but the energy gain could be lost if a secondary loop system required by safety considerations is used. However, its overall climate impact, expressed in TEWI, is still significantly lower than that of HFC-134a and in the same order of magnitude of CO_2 systems. The principle barriers to commercialization at the present time are the resolution of the flammability risk and the assurance of a commercial global availability of HFC-152a.

Table TS-17 presents a comparison of the primary MAC systems currently in use, under development or demonstrated. For each option, issues of relative cost are indicated, along with points that need to be considered to evaluate the effects on the radiative forcing of the climate system, including the indirect effects. It has to be emphasized that the choice of a given technical option in a given year will have only a limited effect in the first years of introduction due to all the refrigerant banked in – and emitted by – the current fleet.

4.4 What are the most important findings for foams?

What applications are foams currently used for and why?

Foamed (or cellular) polymers have been used historically in a variety of applications that utilize the potential for creating either flexible or rigid structures. Flexible foams continue to be used effectively for furniture cushioning, packaging and impact management (safety) foams. Rigid foams are used primarily for thermal insulation applications such as those required for appliances, transport and in buildings. In addition, rigid foams are used to provide structural integrity and buoyancy.

For thermal insulation applications (the majority of rigid foam use), mineral fibre alternatives (e.g. glass fibre and mineral wool) have been, and continue to be, major not-in-kind alternatives. Table TS-18 illustrates the major benefits and limitations of both approaches.

The implications of these relative benefits and limitations vary substantially, both between products within a category and between applications. This makes a generic conclusion about

Table TS-18. Benefits and limitations of the use of both mineral fibres and cellular polymers in thermal insulation applications.

	Mineral Fibre	*Cellular Polymers*
Benefits	• Initial cost • Availability • High max. temperature • Fire performance	• Blowing-agent-based thermal properties • Moisture resistance • Structural integrity • Lightweight
Limitations	• Air-based thermal properties • Moisture resistance[a] • Low structural integrity	• Fire performance (organic) • Limited max. temperature • Initial cost (in some cases)

Notes:
[a] Potential effect on long-term thermal performance

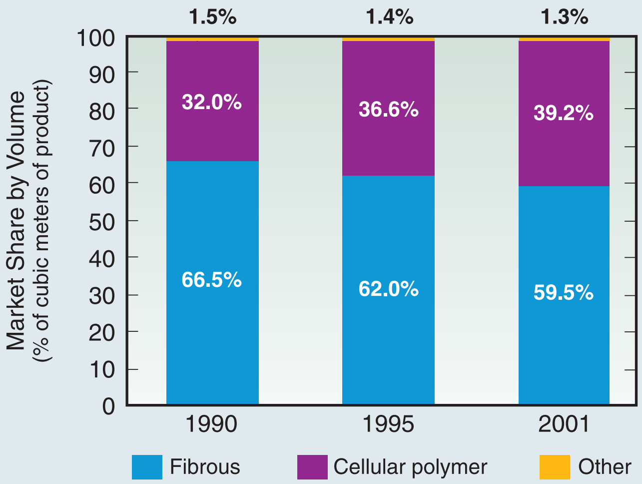


Figure TS-12. Variation of insulation volume by product type (1990–2001) in Europe.

preferences impossible. The current thermal insulation market supports a variety of solutions (at least 15 major product types), and this reflects the range of requirements demanded for the applications served. Unfortunately, there are only limited data available on the thermal insulation market at global and regional levels. One of the complexities of global market analysis is the difference in building practices around the world, which often respond to material availability and climatic conditions.

Purely as an example, a systematic and periodic analysis of the European thermal insulation market has enabled the trends over the period from 1990–2001 to be identified (Figure TS-12). This analysis indicates a growing reliance on foamed products in thermal insulation applications that has been driven in part by the increased use of metal-faced panels in Europe, which in turn relies increasingly on foamed cores. However, the harmonization of fire classifications in Europe over the coming 5 years may cause the trend to be arrested or even reversed. Such is the volatility of these markets and the importance of maintaining ranges of product types.

In reviewing the not-in-kind options, it is important to acknowledge continuing development. For example, it seems likely that the use of vacuum insulation panels (evacuated and sealed foam matrices) in domestic refrigerators and freezers will increase. In fact, most Japanese units already contain at least one such panel in strategic design positions. Other opportunities include multilayer reflective foils but the thermal efficiency of these is, as yet, far from proven.

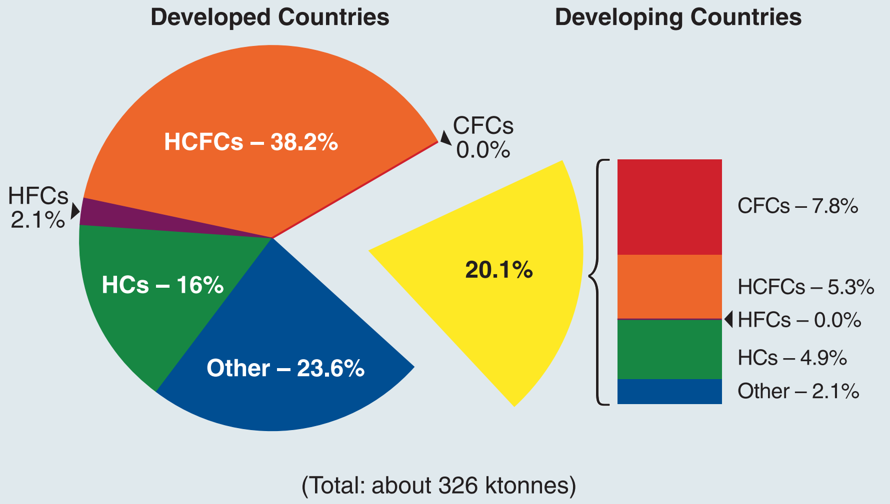
The relationship between foam products, processes for manufacture and applications is complex. Table TS-19 summarizes the main interrelationships between generic product types and applications for both non-insulating and insulating foams, while the main chapter deals with the additional overlay of processes for manufacture.

Table TS-19. Main interrelationships between generic product types and applications for both non-insulating and insulating foams.

Foam type *(insulating)*	**Application Area**							
	Refrigeration and transport			**Buildings and building services**				
	Domestic appliances	Other appliances	Reefers and transport	Wall insulation	Roof insulation	Floor insulation	Pipe insulation	Cold stores
Polyurethane	√	√	√	√	√	√	√	√
Extruded polystyrene			√	√	√	√	√	√
Phenolic				√	√		√	√
Polyethylene						√	√	

Foam type *(non-insulating)*	**Application area**					
	Transport		**Comfort**		**Packaging**	**Buoyancy**
	Seating	Safety	Bedding	Furniture	Food and other	Marine and leisure
Polyurethane	√	√	√	√	√	√
Extruded polystyrene					√	√
Polyethylene					√	√

Figure TS-13. Breakdown of blowing-agent use by type and country type (2001).

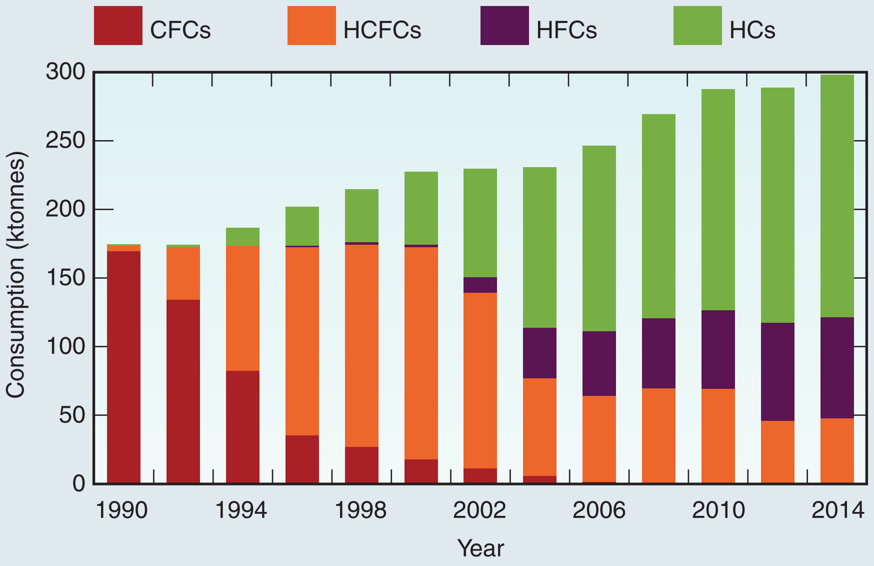


What blowing agents have been used historically and what are the trends for the future?

At the point of discovery of the ozone hole in the early 1980s, virtually all of the applications and product types listed above used CFCs as either a primary blowing agent (rigid foams) or auxiliary blowing agent (flexible foams). The total consumption of CFCs by the foam sector in 1986 was approximately 250 ktonnes (165 ktonnes rigid; 85 ktonnes flexible). Blowing-agent use overall grew by a further 30% over the next 15 years, despite improved blowing efficiencies and reduced losses. In the meantime, however, a variety of alternative blowing agents have been evaluated and adopted. These include HCFCs (as transitional substances), hydrocarbons, HFCs, methylene chloride (for flexible foams) and various forms of CO_2. Figure TS-13 summarizes the situation in 2001.

Figure TS-14 illustrates the projected growth of blowing-agent consumption in the rigid foam sector for the period to 2015.

Figure TS-14. Projected growth in blowing-agent consumption in rigid foams – beyond 2000.



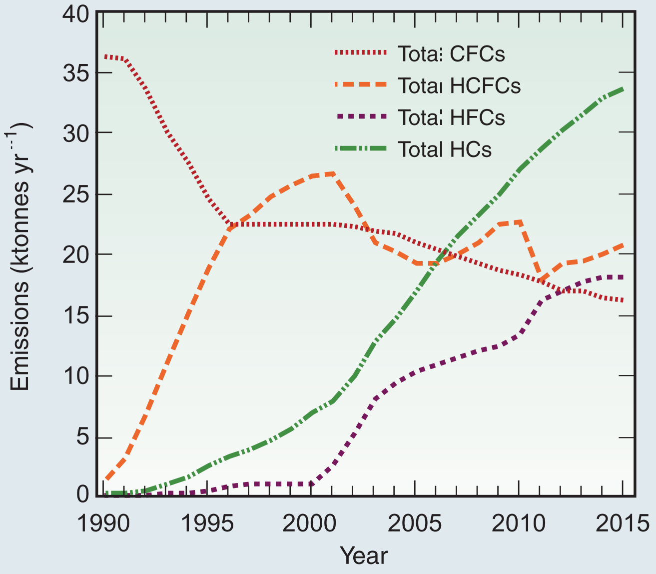


Figure TS-15. Annual global blowing-agent emissions by group (1990–2015).

What are the implications of past, present and future use patterns?

Past, present and future use patterns have impacts on both emissions and the accrual of banked blowing agents. Figure TS-15 illustrates the projected emissions between 1990 and 2015 based on the historical and future use of blowing agents in foam. The graph shows the projected annual emission of all blowing-agent types up to 2015. Table TS-20 assesses the projected development of banks by region and application area. It is clear that much of the emissions from the foams used in buildings has yet to take place.

What drives the selection of blowing agents?

Thermal conductivity

The ability to retain blowing agents within foams provides opportunities to improve the efficiency of the thermal insulation relative to air-filled products. However, such benefits can only be achieved when the thermal conductivities of the retained blowing agents are lower than that of air. This is the case for all blowing agents highlighted in the Figure

Table TS-20. Total global accrued banks of blowing-agent types by group (1990–2015).

Application area	**Blowing agent**	**1990 (tonnes)**		**2000 (tonnes)**		**2015 (tonnes)**	
		Developed Countries	**Developing Countries**	**Developed Countries**	**Developing Countries**	**Developed Countries**	**Developing Countries**
Appliances and transport	*CFC*	378,000	108,000	238,000	222,000	450	15,500
	HCFC	0	0	177,000	32,100	75,700	265,000
	HFC	0	0	1150	0	154,000	0
	HC	0	0	87,100	31,600	354,000	329,000
	All agents	378,000	108,000	503,250	285,700	584,150	609,500
		(24.6%)	(53.7%)	(20.1%)	(58.1%)	(17.2%)	(58.5%)
Polyurethane panel subtotal	*CFC*	233,000	34,300	283,000	70,500	262,000	75,100
	HCFC	0	0	96,000	3700	142,000	94,800
	HFC	0	0	2150	0	135,000	0
	HC	0	0	43,800	250	238,000	0
	All agents	233,000	34,300	424,950	74,450	777,000	169,900
		(15.1%)	(17.1%)	(16.9%)	(15.1%)	(22.9%)	(16.3%)
Buildings and other subtotal	*CFC*	921,000	58,800	964,000	127,300	769,000	106,000
	HCFC	5200	0	568,000	4650	683,000	156,000
	HFC	0	0	200	0	269,000	150
	HC	1150	0	47,500	50	311,000	0
	All agents	927,350	58,800	1,579,700	132,000	2,032,000	262,150
		(60.3%)	(29.2%)	(63.0%)	(26.8%)	(59.9%)	(25.2%)
Total	*CFC*	1,532,000	201,100	1,485,000	419,800	1,031,450	196,600
	HCFC	5200	0	841,000	40,450	900,700	515,800
	HFC	0	0	3500	0	558,000	150
	HC	1,150	0	178,400	31,900	903,000	329,000
	All agents	1,538,350	201,100	2,507,900	492,150	3,393,150	1,041,550

TS-15. However, the relative performance of the various blowing-agent types does vary with temperature; for example, the comparative advantages of HFCs over hydrocarbons are greater in refrigerators (average temperature of 5°C) than in water heaters (average temperature of 40°C). In addition, the size and shape of the cells also affects the overall performance of the foams and, therefore, product comparisons are not always straightforward.

Flammability (product and process)
The overall flammability of a foam product is influenced by the choice of polymeric matrix and facing material as well by the choice of blowing agent. However, it is often the case that the contribution of the blowing agent can shift the classification of a product or can change the attitude of insurers to the risk posed. In addition, the handling of certain flammable blowing agents can create fundamental challenges in some foam processes. This is particularly the case for small and medium enterprises (SMEs), for which economies of scale do not exist and discontinuous processes dominate. In the case of flammable blowing agents, investment criteria vary considerably depending on whether the investment relates to a new plant or modification of an existing plant. In the latter case, costs can often be prohibitive if the plant is old or if it is owned by a small or medium enterprise. Employer liability issues can also be a cause for concern in some regions with a strong litigious heritage.

What has already been done to minimize use?

When the three aspects presented above are taken into consideration, HFCs emerge as the preferred option in several key sectors, although the progress made in developing alternative technologies has ensured that uptake has been constrained. An example of this is the continuing extension of the application of hydrocarbon technologies. However, even in cases where HFCs have been adopted, there are two additional points to consider:

(1) How much HFC is required in the formulation to achieve the required performance?
(2) Which HFC should be chosen?

The cost of HFCs can be a general constraint on uptake. Blowing-agent costs typically represent a significant element of overall variable costs. Accordingly, any substantial elevation in blowing-agent costs can influence variable costs by up to 15%. In a highly competitive market, such increases are unsustainable and prevent selection, unless formulation changes can be made to reduce dependence on the more expensive blowing agent. An example of this is the co-blowing of HFC-based polyurethane foams with CO_2 generated from the reaction of isocyanate and water.

Nonetheless, the overall decision is a complex one based on combinations of direct blowing-agent cost, related formulation issues (e.g. the use of increased flame retardant or foam density penalties), product performance, process safety and capital costs. As noted previously, the latter are particularly relevant to SMEs and other small volume consumers.

The net effect of the above selection of considerations on HFC demand has been to reduce previous (1999) projections of 115 ktonnes consumption in 2010 to 60 ktonnes in 2010 in this current report. This can already be considered as a reduction facilitated by the application of responsible use principles by the foam industry.

Lowest GWP selection
Since the two prime liquid HFCs (HFC-245fa and HFC-365mfc) have similar 100-year GWPs, the choice between the two has been driven more by a consideration of respective boiling points and blowing efficiencies. For gaseous blowing agents, HFC-152a has a much lower 100-year GWP than HFC-134a. However, HFC-152a is more flammable than HFC-134a and is also emitted much faster from some types of foam (e.g. extruded polystyrene). This can mean that short-term impacts of HFC-152a use can be as significant as those of HFC-134a. In addition, the thermal insulating benefit of HFC-152a can be short-lived. All of these factors have to be evaluated during the selection of the appropriate blowing agent.

What additional measures can reduce future emissions further and what actions are required?

Further substitution
While the adoption of responsible use criteria in HFC selection has successfully reduced the consumption of HFCs in the foam sector by nearly 50% over that predicted in 1999, there are several areas in which further substitution may be possible over the next 5–10 years. For example:

- wider hydrocarbon use in polyurethane spray foam;
- wider CO_2 use in extruded polystyrene (XPS);
- wider hydrocarbon use in appliance foams;
- changes in the attitude of insurers to hydrocarbons in panels.

Although the impacts of each of these trends can be modelled individually, the uncertainties are too great to be meaningful. Accordingly, in this assessment, two high-level mitigation scenarios are presented to evaluate the impact of pursuing such options.

Process of good practice
Work has already been initiated on establishing procedures for the identification and minimization of process losses. While this work is important in setting the right tone for the handling of HFCs in foam processes, the potential savings are unlikely to reach more than 2–3% of total life-cycle emissions, since most processes are already well enclosed. One

exception might be in the emissions during polyurethane spray application, where further effort is still required to quantify losses; future efforts may lead to improvements in spray head design.

Waste management

Waste minimization is a clear objective of all businesses. However, foam manufacturers face specific challenges:

- product proliferation requiring more versatile production processes;
- intrinsic fabrication losses (e.g. cutting pipe sections from block foam).

The management of this waste is therefore a key issue in minimizing emissions. The mitigation-scenario models assess the effects of a combination of process and waste management improvements.

Bank management (refrigerators)

The size of existing and future banks of blowing agent in the appliance and transport sectors has been estimated. The baseline scenario already takes into account the recovery activity occurring in Europe and Japan, so bank sizes do not automatically equate to future emissions. With proven technology and the cost of recovery from refrigerators currently estimated at 10–50 US\$/tCO_2-eq, it would appear reasonable to assume that all refrigerator foams could be managed at end-of-life by 2015, if the investment in plants to do so were appropriately dispersed geographically. This would, however, involve investment in developing as well as developed countries. One scenario evaluated in this report examines the potential impact of all appliances being processed at end-of-life with anticipated recovery levels in excess of 80% of the original blowing-agent loading.

Bank management (buildings)

For the building sector, the technical feasibility and economic viability of blowing-agent recovery is less well established. Activities such as the Japan Testing Center for Construction Materials (JTCCM) project in Japan are assisting the development of further knowledge in this area. At present, however, the general consensus is that recovery will be considerably more expensive than from appliances because of the lower yield (caused by losses in the use and recovery phases) and the additional costs of demolition waste separation.

One exception to this trend is in the metal-faced panel market where blowing-agent retention and ease of dismantling may allow recovery through existing refrigerator plants. The bank available from polyurethane panels has been assessed and is expected to exceed 700 ktonnes in fluorocarbon blowing agents by 2015. Recovery costs are expected to be in the same range as for appliances, but work is continuing to confirm this. Both scenarios have been modelled, but with a more modest expectation of 20% recovery from traditional building sources.

What is the significance of these potential scenarios to wider climate and ozone strategies?

The baseline emissions for the BAU scenario are shown in Figure TS-16. Because the life cycles of foams are so significant, all graphs in this section illustrate the likely impact of possible emission reduction scenarios up to 2100. The baseline assumption is a freeze at 2015 consumption levels for both HCFCs and HFCs. It is assumed that HCFCs are phased-out linearly between 2030 and 2040. Bearing in mind that technology developments are likely to continue in the foams sector, reliance on HFCs is not expected beyond 2030, and a linear decline is assumed from 2020. As a further reference point, the ongoing emissions from the banks already established at 2015 are also shown. The three primary elements of the mitigation scenario can be summarized as follows:

- a linear decrease in the use of HFCs between 2010 and 2015, leading to a 50% reduction by 2015;
- the adoption of production emission reduction strategies from 2005 onwards for all block foams and from 2008 onwards in other foam subsectors;
- the extension of existing end-of-life measures to all appliances and steel-faced panels by 2010 together with a 20% recovery rate from other building-based foams from 2010.

The resulting impacts of these three measures are as shown in Figure TS-17 and Table TS-21.

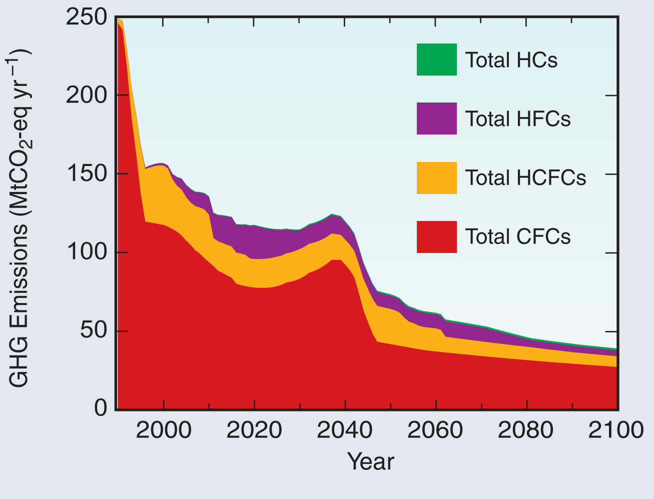


Figure TS-16. GWP-weighted blowing-agent emissions by group (1990–2100) – business-as-usual scenario.

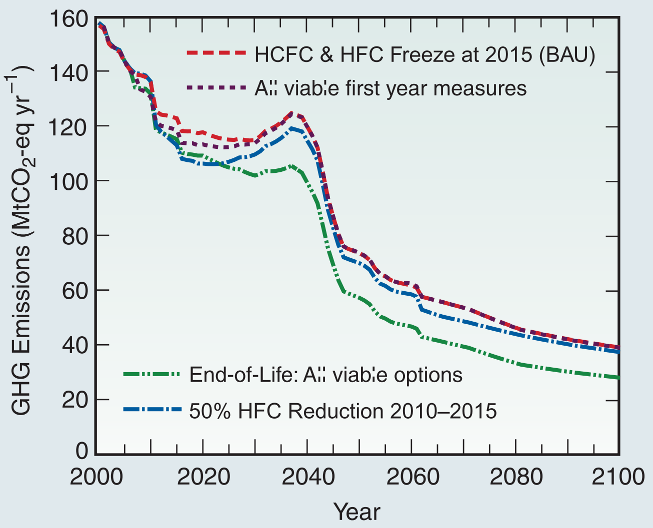


Figure TS-17. Summary of impacts of individual packages of measures.

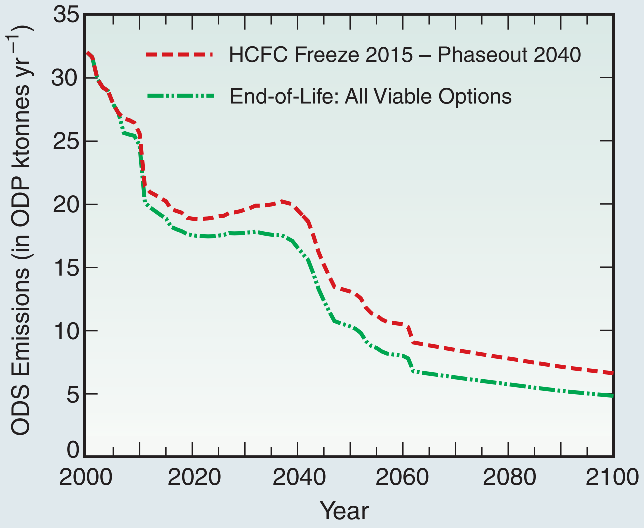


Figure TS-18. Impact of all viable end-of-life measures on ODS emission reduction.

It can be seen that focusing on reducing HFC consumption provides the most significant saving in the period up to 2015 and, on the basis that any such reduction is extrapolated out to use patterns beyond 2015, this focus offers the greatest 'HFC-specific' benefit to 2100 as well. In contrast, end-of-life measures deliver lower savings during the period up to 2015, but they do have the potential to deliver more overall savings in the period up to 2100 if all blowing-agent types are considered. The value is particularly significant for CFCs, for which the GWPs are high and there is an incremental effect of ozone depletion.

The potential savings in ODSs emissions from all viable end-of-life strategies is shown n Figure TS-18 based in ODP tonnes. It can be seen that year-on-year savings in the order of 2000–3000 ODP tonnes will accrue for the period to 2100.

Table TS-21. Summary of impacts of individual packages of measures by blowing agent type: cumulative emission reductions resulting under each scenario assessed.

Measure	Year	Cumulative Emission Reductions			
		CFCs (tonnes)	HCFCs (tonnes)	HFCs (tonnes)	CO_2-equivalents ($MtCO_2$-eq)
HFC consumption reduction (2010–2015)	2015	0	0	31,775	36
	2050	0	0	225,950	259
	2100	0	0	352,350	411
Production/installation improvements	2015	78	14,450	16,700	36
	2050	58	31,700	32,700	68
	2100	47	24,350	26,500	55
End-of-life management options	2015	8545	16,375	105	52
	2050	64,150	144,650	88,540	540
	2100	137,700	358,300	194,800	1200

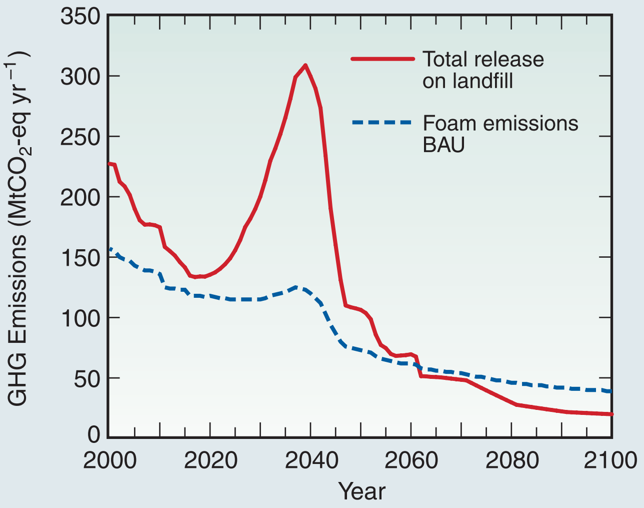


Figure TS-19. The effects of applying different initial landfill emission assumptions.

The estimates for reductions in both GHG and ODS emissions identified in this analysis from end-of-life measures are relatively conservative, since they are measured against a baseline where only 10–20% of blowing loss is accounted for when the foam is land-filled. This partially explains why there are significant emissions after 2065. Effectively, the landfill sites have become banks of their own. If a more aggressive assumption were to be applied to foams destined for landfill (i.e. 100% emission at the point of landfill), Figure TS-19 illustrates the consequence in GHG emission terms.

While it is recognized that the truth probably lies somewhere between the two extremes, the potential release of such significant amounts of blowing agent over a relatively short period (2030–2050) draws attention to the potential incremental value of end-of-life management as a mitigation option.

4.5 What are the most important findings for medical aerosols?

Medical aerosols are important in the treatment of asthma and COPD

Asthma and chronic obstructive pulmonary disease (COPD) are the most common chronic diseases of the air passages (airways or bronchi) of the lungs and are estimated to affect over 300 million people worldwide. These illnesses account for high health care expenditure and cause significant loss of time from work and school and, in addition, COPD is responsible for premature death.

Asthma is a chronic condition with two main components, airway inflammation and airway narrowing. Most asthma patients have symptoms every day, with more severe attacks intermittently. Asthma most often starts in childhood, and prevalence varies from approximately 1% in some countries such as Indonesia to over 30% in children in New Zealand and Australia.

COPD is a condition typified by narrowing and inflammation of the airways in conjunction with damage to the lung tissue. It is caused primarily by cigarette smoking, with environmental air pollution as a potential cofactor, and ultimately leads to permanent disability and death. The prevalence of COPD in many developed countries is between 4–17% in adults over 40 years old. Data are less certain in developing countries, but figures as high as 26% have been quoted. Smoking is declining in some developed countries, but in developing countries both smoking and COPD are increasing.

Inhaled therapy is currently and likely to remain the gold standard for treatment. Inhalation of aerosol medication of a specific particle size (1–5 microns) optimizes the local clinical effect in the airways where it is needed, with minimal side effects. Inhalation aerosols have been the subject of significant investment in research and development, in response to both therapeutic and environmental needs. Currently the two main methods of delivering respiratory drugs for most patients are the metered dose inhaler (MDI) and the dry powder inhaler (DPI).

What is a MDI?

MDIs are the dominant form of treatment for asthma and COPD worldwide. The MDI was introduced in the mid-1950s with CFC-11 and CFC-12 as propellants; CFC-114 was introduced later. In order to accomplish the phase-out of CFCs under the Montreal Protocol, the MDI industry undertook an exhaustive search for an appropriate alternative aerosol propellant. A medical propellant must be safe for human use and meet several additional strict criteria related to safety and efficacy: (1) liquefied gas with appropriate vapour pressure, (2) low toxicity, (3) non-flammable, (4) chemically stable, (5) acceptable to patients (in terms of taste and smell), (6) appropriate solvency characteristics and (7) appropriate density. It was extremely difficult to identify compounds fulfilling all of these criteria and in the end only two HFCs – HFC-134a and HFC-227ea – emerged as viable alternatives to CFCs.

The components and formulations of CFC-based MDIs had to be substantially modified to use the new HFC propellants. As drug devices, MDIs are subject to extensive regulation by national health authorities to ensure product safety, product efficacy and manufacturing quality. Therefore, the process for developing HFC MDIs is essentially the same as the development of a wholly new drug product in that it involves full clinical trials for each reformulated MDI. The development (technical, pharmaceutical, clinical) costs for the CFC-to-HFC transition were estimated to be approximately US$ 1 billion in 1999 and hence now will be significantly higher. Similar costs would be expected for de-novo DPI development programmes to replace existing molecules in MDIs.

What is a DPI?

DPIs deliver powdered medication of specific particle size, do not use propellants and have no impact on the ozone layer or climate. Delivery of the active drug in powder form is technically difficult. For example, particles of respirable size tend to have poor flow characteristics due to adhesive interparticle forces. Additionally, most DPI formulations are sensitive to moisture during processing, storage and in use, thereby limiting their utility in humid climates.

Early DPIs providing single premeasured doses had limited use in the 1960s and 1970s. Significant technical progress has led to patient-friendly multidose DPIs becoming more widely available in the past decade, and this has mitigated the increase in MDI use. DPIs have been formulated successfully for many inhaled drugs and are now widely available in many but not all countries. However, they are not an alternative to pressurized MDIs for all patients or for all drugs.

The relative cost of DPIs is high, especially compared with MDIs containing salbutamol, which still account for approximately 50% of the MDIs prescribed worldwide. In a study conducted to compare the costs across seven European countries, the salbutamol DPIs were found to cost on average 2.6 times more than MDIs.

What factors influence treatment choice?

Primary prevention of asthma is not yet feasible, while primary prevention of COPD entails not commencing tobacco smoking. The prevalence of asthma and COPD is likely to continue to increase.

The choice of the most suitable drugs and inhaler are decided by physician and patient based on many factors including disease and severity, compliance, ease of use, cost, availability and patient preference. Inhaler devices are only effective if used correctly. Patients will often be able to use one device correctly but not another. Both MDIs and DPIs have an important role in treatment, and no single delivery system is universally acceptable for all patients. It is critical to preserve the range of therapeutic options.

MDIs are the dominant form of treatment for asthma and COPD worldwide. In developed countries, the proportion of current MDI to DPI use varies substantially between countries: in the USA, 9:1 (MDI:DPI); in the UK, 7:3; in Sweden, 2:8. This relates to a number of factors, including availability (e.g. multidose DPIs are only recently available in the USA compared with a local company with a long tradition of DPI manufacture in Sweden) and affordability.

What are the future technical developments?

Annual growth in the global market in inhaled asthma/COPD medication up to 2015 is projected at approximately 1.5–3% yr^{-1}. A large portion of CFCs are being replaced by HFCs (approximately 90% HFC-134a and 10% HFC-227ea), and all MDI use in the developed world will be HFC by 2010. From a peak annual CFC use of over 15,000 tonnes in 1987–2000, CFC use in MDIs has fallen to an estimated 8000 tonnes, with HFC accounting for 3000–4000 tonnes, in the period 2001–2004, and by 2015, HFC use is estimated to rise to 13,000–15,000 tonnes. The lower use of HFCs compared to peak CFC use is partly due to increased use of DPIs and partly because some HFC MDIs use less propellant per actuation.

No major technical breakthroughs in device technology are expected in the short-term. Research and development for a new inhalation product is a lengthy, technically challenging and expensive process and typically takes over 10 years to reach the market. Future inhalation devices such as nebulizers and DPIs with a power source to make them independent of a patient's breath or small aqueous multidose devices will probably be more expensive than present-day DPIs and will therefore be even more expensive than HFC MDIs

In developing countries, inhaled therapy is almost exclusively with pressurized MDIs, either from multinational or local manufacturers. Improved economic circumstances together with the adoption of international treatment guidelines will likely substantially increase inhaled therapy. Affordable and less complex DPIs are technically feasible and could be manufactured locally in developing countries. There would be significant pharmaceutical difficulties in hot and humid climates, and they would remain more expensive than MDIs on a cost-per-dose basis. If these became available and achieved a significant market share, they could mitigate the future increases in volumes of HFC needed for MDIs.

What would be the cost of a complete switch from HFC MDIs to DPIs?

Typically, newer multidose DPIs contain more expensive drugs, whereas about 50% of MDIs contain salbutamol, which is less expensive and off patent. This explains part of the difference in individual inhaler cost. It has been estimated that by 2015 there could be as many as 340 million HFC MDI units containing salbutamol. Switching these to an equivalent salbutamol DPI would incur significant costs to health care systems. Hypothetical estimates of the cost of switching completely from HFC MDIs to DPIs (assuming a minimal twofold increase in price) would be on the order of an additional and recurrent US$ 1.7–3.4 billion yr^{-1} (150–300 US$/$tCO_2$-eq). The emission reduction achieved would be about 10 $MtCO_2$-eq yr^{-1} by 2015. This additional cost would significantly impact on patient care.

Would there be any medical constraints for a switch from HFC MDIs to DPIs?

Switching patients from reliable and effective medications has significant implications for patient health and safety, and the provision of a range of safe alternatives is critical before enforcing change on environmental grounds. Any future environmental policy measures that could impact on patient use of HFC MDIs would require careful consideration and consultation with physicians, patients, national health authorities and other health care experts.

What the are key conclusions?

- The major impact in reducing GWP with respect to MDIs is the completion of the transition from CFC to HFC MDIs.
- No major breakthroughs for inhaled drug delivery are anticipated in the next 10–15 years given the current status of technologies and the development time scales involved.
- The health and safety of the patient is of paramount importance in treatment decisions and in policy making that might impact those decisions.
- Based on the hypothetical case of switching the most widely used inhaled medicine (salbutamol) from HFC MDIs to DPI, the projected recurring annual costs would be in the order of US$ 1.7 billion with an effective mitigation cost of 150–300 US$/$tCO_2$-eq for a reduction of about 10 $MtCO_2$-eq yr^{-1} by 2015.

4.6 What are the most important findings for fire protection?

What are past and current trends in fire protection?

Halons are gases that display exceptional safety, efficiency and cleanliness in fire-fighting applications. These gases were widely used worldwide in both fixed and portable fire-extinguishing equipment beginning in the early 1960s. Because of their high ODPs, governments and fire protection professionals led the first sector-wide phase-out under the Montreal Protocol. This led to the development of a range of effective alternatives for new systems. Since fire protection is a highly regulated sector, adopting alternatives requires extensive changes in local, national and international standards, practices and technology. These changes have reduced unnecessary emissions from the halon bank and are also being applied to the halon alternatives.

There are two categories of applications that can require halon or an alternative: fixed systems and portable extinguishers. Halon 1301 dominated the market in fixed systems prior to the Montreal Protocol, and its remaining bank was about 45 ktonnes in 2000. Halon 1211 was primarily used in portable extinguishers, and the bank in 2000 was estimated at about 154 ktonnes. Halon 2402 was used predominantly in the former Soviet Union, and no information on banks or emissions is available in the literature. One estimate of 2000 emissions is 2.3 ktonnes for halon 1301 and 17.8 ktonnes for halon 1211, or about 5% and 11% of the bank per year, respectively. One study suggests that the emission rate for halon 1301 in fixed systems, excluding ships, aircraft and military systems, is as little as 0.12% yr^{-1} when an exceptional level of diligence is made in tracking and keeping the halon in place for providing critical fire protection. An extremely low (0.12% yr^{-1}) rate of emissions has been achieved in one region, primarily due to unique cultural factors together with unusually strong enforcement action, both of which may be difficult to replicate in other regions. On average, emission rates for fixed systems are about 2 ± 1% yr^{-1} and about twice that for portable extinguishers, that is, 4 ± 2% yr^{-1} of the bank (installed base including stocks for recharge).

Fire protection is strictly regulated in most countries. New agents/techniques can only be used following a demonstration of acceptable safety and fire-extinguishment performance according to specific protocols. It is important that countries without national standards strive to adopt the practices recommended in international standards in order to protect against the introduction of unsafe or ineffective alternatives.

Selecting an alternative to halon involves evaluating a wide range of factors. These include space and weight, cost, safety, requirements for 'cleanliness' (i.e. without residue or damage such as in the storage of records or cultural heritage buildings), environmental performance, effectiveness against a specific fire threat (fires in solid materials ('Class A' fires), flammable liquids ('Class B' fires) and energized electrical equipment ('Class C' fires) and special circumstances (e.g. very cold conditions).

Halon is no longer necessary in most (>95%) new installations that would have used halons in pre-Montreal Protocol times. The remaining new installations still using halons are principally in commercial aircraft and some military applications for which an effective alternative to halons has yet to be found. Among the applications formerly protected by halons, about half of today's new installations are based upon non-gaseous alternatives, such as water and dry powders, while the other half make use of in-kind gaseous agents, including a range of halocarbons and inert gases.

In fixed systems where a clean agent is necessary, the alternatives currently available are CO_2, inert gases (such as nitrogen and argon), HFCs, PFCs, HCFCs and, more recently, a fluoroketone (FK). Some of these alternatives have no significant effect on the climate system, while others have substantial GWPs. Only the HCFCs are also ozone-depleting. PFCs and HCFCs were used in the early stages of implementation of the Montreal Protocol but do not provide any advantage over other halocarbon clean agents. New PFC systems are no longer being produced due to the environmental impacts of these gases upon the climate relative to other alternatives with similar capabilities and costs. CO_2 systems may be appropriate for some applications but are lethal at concentrations necessary to extinguish fires, while inert gas systems may also be appropriate for use in some applications but have significant weight and volume impacts and are not recommended when speed of fire suppression is an issue, due to a discharge rate that is five to six times slower than that of halocarbon systems.

Table TS-22 presents a comparison of the primary systems currently in use, under development or demonstratied for clean, fixed systems of fire extinguishment suitable for occupied spaces (typically replacing halon 1301). For each option, issues of relative cost are indicated, along with considerations needed to evaluate the effects on the radiative forcing of the climate system and practical concerns such as system weight and space requirements, special capabilities and availability.

Figure TS-20 is an illustration of the production, emission levels and resultant bank sizes of halon 1301 and its HFC/PFC/HCFC/FK alternatives for the period 1965–2015. The bank of Halon 1301 in 2002 is projected to be 42,434 tonnes with 2052 tonnes of emissions, which agrees well with atmospheric measurements indicating 1000–2000 tonnes of emissions. The combined bank of all HFC/PFC/HCFC/FK alternatives in fixed systems in 2004 is estimated to be approximately 26,700 tonnes. PFCs make up about 2.5% of that total. By one estimate, the HCFC portion can be as high as approximately 3600 tonnes (about 13%). Studies suggest that emission rates of $2 \pm 1\%$ $year^{-1}$ are now practical in these systems. At a 2% emission rate, the 2004 emissions represent 1.4 million tonnes of CO_2-equivalent ($MtCO_2$-eq).

For portable extinguishers, fire codes and costs are the primary drivers in choosing an alternative (typically replacing Halon 1211). Portable extinguishers employing HFCs and PFCs have found limited market acceptance due primarily to their high costs compared to more traditional extinguishing agents such as CO_2, dry chemicals and water. HCFC acceptance has been greater but is also limited by its high cost relative to those of more traditional agents. Dry chemical agents are between about six and sixteen times cheaper than the clean agents and are most effective in terms of fire ratings, but they have the disadvantage of agent residue. HFCs, PFCs and HCFCs are the most expensive and least effective in terms of fire-extinguishing performance (i.e. their fire ratings). Table TS-23 presents a comparison of the alternative portable fire extinguishers. For each option, relative cost and climate considerations are indicated as well as practical concerns such as weights and dimensions. Users of Halon 1211 portable extinguishers in the past currently have three choices: a single HFC/HCFC extinguisher at increased cost, a single dry chemical extinguisher if the residue can be tolerated or two extinguishers – one of water for ordinary combustibles, and a second of CO_2 for use in flammable liquid fires or near electrically energized equipment. Local and national regulations often dictate the choice of portable extinguishers.

Figure TS-21 is an illustration of the production, emission levels and resultant bank sizes of Halon 1211 and its HFC/PFC/HCFC alternatives for the period 1965–2015. The Halon 1211 bank in 2002 is projected to be 124,843 tonnes with 17,319 tonnes of emissions. This is approximately twice the 7000–8000 tonnes of emissions one would expect based on atmospheric measurements. While no data are available in the literature, information provided by a producer combined with modelling, estimates the portable extinguisher bank of HCFCs, HFCs and PFCs at approximately 1471 tonnes at the end of 2002 with 0.12 $MtCO_2$-eq of emissions. The estimate for 2004 is approximately 1852 tonnes with emissions of 0.16 $MtCO_2$-eq at a 4% emission rate. Approximately 68% are HCFCs, 30% are HFCs and 2% are PFCs.

Table TS-22. Comparison table – clean-agent systems suitable for occupied spaces.

Fixed systems	**Halon 1301 (reference)**	**HFC-23**	**HFC-227ea**	**HFC-125[1]**	**FK- 5-1-12**	**Inert Gas**
Substance characteristics						
Radiative efficiency (W m^{-2} ppb^{-1})	0.32	0.19	0.26	0.23	0.3	n.a.
Atmospheric lifetime (yr)	65	270	34.2	29	0.038	n.a.
Direct GWP (100-yr time horizon)						
- This report	7030	14,310	3140	3450	not available[2]	n.a.
- IPCC (1996)	5400	11,700	2900	2800		
Ozone depletion potential	12	~0	-	~0	-	n.a.
Technical data						
Demonstrated special capabilities	yes	yes[3]	yes[4]	yes[4]	note[6]	no
Weight (kg m^{-3})[a]	0.8	2.3	1.1	1.1	1.2	4.3
Area (10^4 m^2/m^3)[b]	5.8	12.0	6.8	7.4	7.3	28.2
Volume (10^4 m^3/m^3)[c]	8.6	18.0	13.1	14.4	13.8	56.6
Emission rate [d]	2 ± 1%	2 ± 1%	2 ± 1%	2 ± 1%	2 ± 1%	2 ± 1%
Costs						
Investment cost (relative to Halon 1301)	100%	535%	377%	355%	484%	458%
Additional service costs ($\mathrm{US\$\ kg^{-1}}$)[e]	0.15	0.43	0.60	0.53	0.72	0.31
Additional recovery costs at end-of-life ($\mathrm{US\$\ kg^{-1}}$) [f] ( ) indicates income	(3.85)	(10.75)	(15.07)	(13.20)	(18.00)	0.00
HFC abatement costs (US\$ per tCO_2-eq)[g]	-	-	-	-	21–22	14–27
Commercial considerations						
Multiple agent manufacturers	-	yes	yes	yes	no[7]	yes

Notes:

[a] Average weight of the agent storage containers and contents in kilogrammes per cubic metre of space protected.

[b] Average area of a square or rectangle circumscribing the agent cylinder bank expressed in square metres × 10^4 per cubic metre of volume protected.

[c] Average volume is the area multiplied by the height of the cylinders measured to the top of the valves expressed in cubic metres × 10^4 per cubic metre of volume protected.

[d] Total average in-service-life annual emissions rate including system discharges for fire and inadvertent discharges.

[e] Additional annual service costs are based on the replacement of 2% of the agent charge emitted per year.

[f] For the halocarbon agents, the end-of-life agent value is positive and represents a cost recovery equivalent to 50% of the initial cost of the agent as the agent is recovered, recycled and resold for use in either new systems or for the replenishment of existing systems.

[g] HFC abatement costs for FK-5-1-12 and inert gas are based on HFC-227ea, the predominant HFC, as the reference. The lower value reflects the cost in US\$ per tonne of CO_2-equivalent at a discount rate of 4% and tax rate of 0%. The range includes both the lowest and highest of costs for the USA, non-USA Annex 1 and non-Annex 1 countries.

Explanation of special capabilities:

1. In some jurisdictions HFC-125 is not allowed for use in occupied spaces while in other jurisdictions that use is permitted under certain conditions.
2. Due to the short atmospheric lifetime, no GWP can be given. It is expected to be negligible for all practical purposes (Taniguchi *et al.*, 2003). See Section 2.5.3.3 'Very short-lived hydrocarbons' for additional information.
3. HFC-23 is effective at low temperatures (cold climates) and in large volumes due to its high vapour pressure.
4. HFC-227ea is effective in shipboard and vehicle applications due to extensive large-scale testing that has established the use parameters and demonstrated its specialized capabilities in these applications.
5. HFC-125 is effective in vehicle and aircraft engine applications as a result of extensive large-scale testing that has established the use parameters and demonstrated its specialized capabilities in these applications.
6. FK-5-1-12 is in the early stages of its product life cycle and has yet to be tested for special applications beyond those achieved through the conventional approval testing of the requirements in ISO and NFPA type standards.
7. While the agent FK-5-1-12 is a proprietary product of a single agent-manufacturer, the agent is available from multiple systems manufacturers.

Figure TS-20. Halon 1301 and halocarbon alternatives time-series for fixed fire-extinguishing systems.

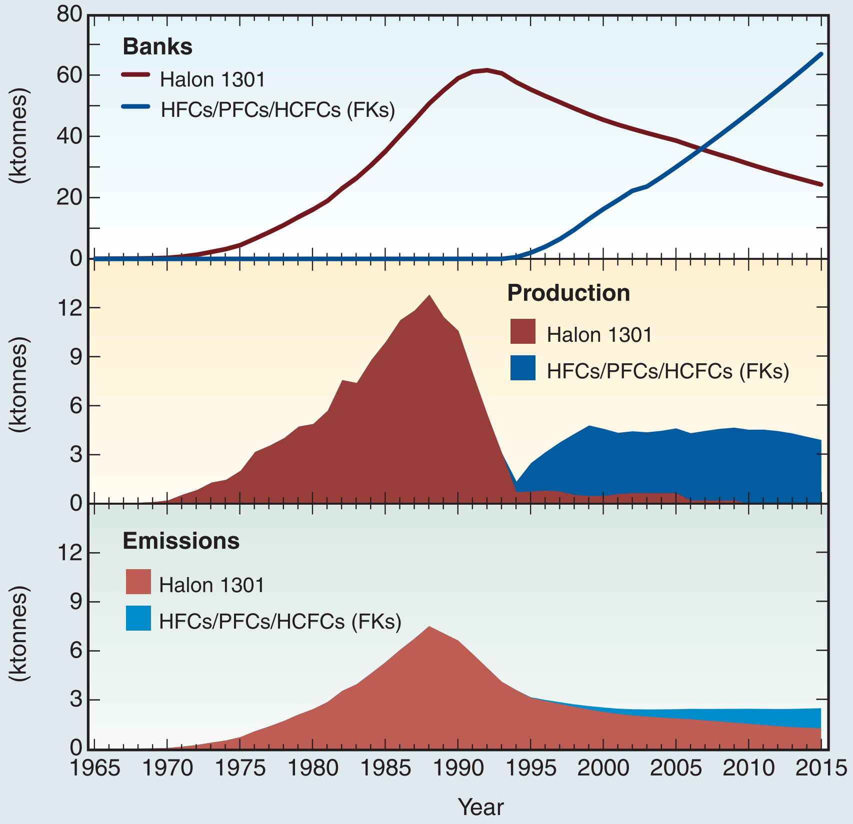


Figure TS-21. Halon 1211 time-series for portable fire-extinguishers.

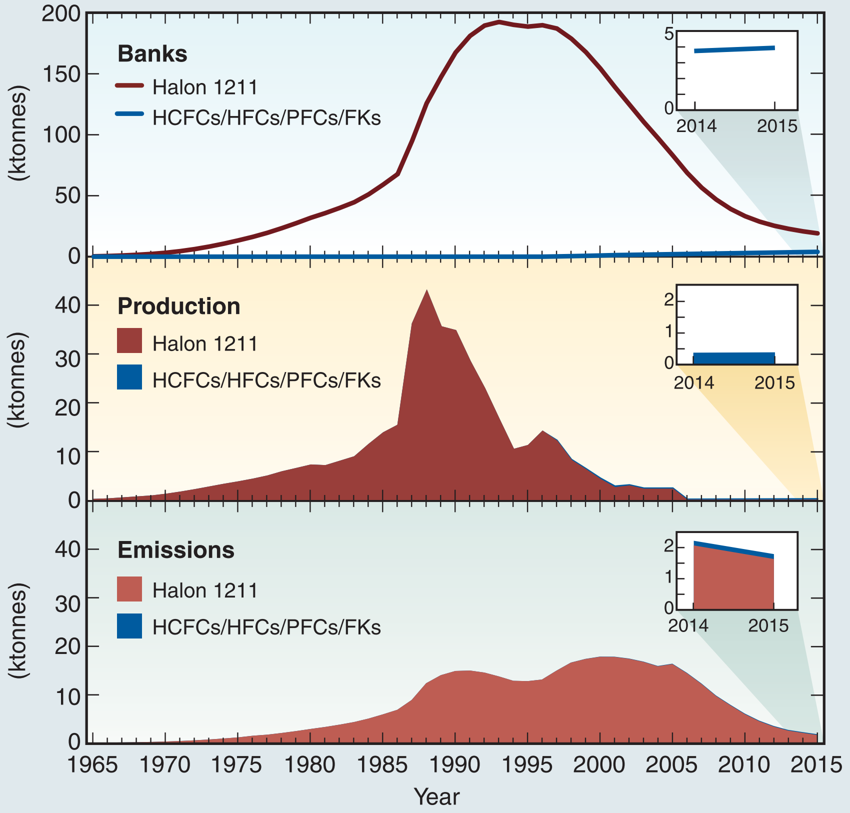


Table TS-23. Comparison table – extinguishing agents for portable fire extinguishers.

Portable systems	Halon 1211 (reference)	HCFC Blend B	HFC-236fa	Carbon Dioxide	Dry Chemical	Water
Substance characteristics						
Radiative efficiency (W m^{-2} ppb^{-1})	0.3	Note[a]	0.28	See Ch. 2	-	-
Atmospheric lifetime (yr)	16	Note[a]	240	See Ch. 2	-	-
Direct GWP (100-yr time horizon)						
- This report	1860	<650[a]	9500	1	-	-
- IPCC (1996)	not given	<730[a]	6300	1	-	-
Ozone depletion potential	5.3	<0.02[a]	-	-	-	-
Technical data						
Agent residue after discharge	no	no	no	no	yes	yes
Suitable for Class A fires	yes	yes	yes	no	yes	yes
Suitable for Class B fires	yes	yes	yes	yes	yes	no
Suitable for energized electrical	yes	yes	yes	yes	yes	no
Extinguisher fire rating [b]	2-A:40-B:C	2-A:10-B:C	2-A:10-B:C	10-B:C	3-A:40-B:C	2-A
Agent charge (kg)	6.4	7.0	6.0	4.5	2.3	9.5
Extinguisher charged weight (kg)	9.9	12.5	11.6	15.4	4.15	13.1
Extinguisher height (mm)	489	546	572	591	432	629
Extinguisher width (mm)	229	241	241	276	216	229
Emission rate [c]	4 ± 2%	4 ± 2%	4 ± 2%	4 ± 2%	4 ± 2%	4 ± 2%
Costs						
Investment costs (relative to Halon 1211)	100%	186%	221%	78%	14%	28%
Additional service costs (US$ kg^{-1})	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]
Additional recovery costs at end-of-life (US$ kg^{-1})	-[d]	-[d]	-[d]	0.00	0.00	0.00

Notes:

[a] HCFC Blend B is a mixture of HCFC-123, CF_4 and argon. While the ratio of the components is considered proprietary by the manufacturer, two sources report that HCFC-123 represents over 90% of the blend on a weight basis, with CF_4 and argon accounting for the remainder. The atmospheric lifetime of HCFC-123 is 1.3 years; this figure is 50,000 years for CF_4.

[b] Fire extinguisher rating in accordance with the requirements of Underwriters Laboratories, Inc. The higher the number, the more effective the extinguisher.

[c] This value is the total average in-service-life annual emissions rate, including both intentional discharges for fire and inadvertent discharges.

[d] This information is neither in the literature nor available from other sources, as it is considered confidential.

What are possible future trends in fire protection?

In 2010 and 2015, emissions of the halocarbon alternatives in fixed fire-extinguishing systems are estimated by modelling to be as high as 2.74 and 3.72 $MtCO_2$-eq, respectively. In portable extinguishers, these emissions are estimated by modelling to be a high as 0.25 and 0.34 $MtCO_2$-eq, respectively. These estimates are based on an emission rate of 2% of the fixed system bank and 4% of the portable extinguisher bank per year and assume a 3% growth rate per year. Efforts to reduce further unnecessary emissions in fire-extinguishing systems could reduce these values by about 50%, while less comprehensive care in emission reductions would likely increase them by 50%. This puts the total emissions from fixed fire-extinguishing systems in the range of 2 ± 1% yr^{-1} and from portable extinguishers in the range of 4 ± 2% yr^{-1}.

While several alternatives to HFCs have been proposed for fire protection, including inert gases, fluoroketones (FKs) and water mist, HFCs and inert gases have become, and appear likely to remain, the most commonly used clean agents and have achieved equilibrium in the market. Due to the lengthy process of testing and approving new fire protection equipment types, no additional options are likely to have an appreciable impact by 2015. FK 5-1-12 has been commercialized and is now available, but there is no basis for predicting its rate of market acceptance or its effect on the already established equilibrium. There is currently no basis for estimating any reduction in the use or emissions of HFC/PFC/HCFCs in fire protection by 2015. In addition, a relationship exists between the halon bank and the use of HFCs. Reductions in the use of halons will result in an increased use of HFCs (and other alternatives) to meet fire protection requirements. Care must continue in the management of the halon bank to ensure an appropriate availability of halons. Therefore, clean agent demand will be influenced by economic growth and by decisions that regulators and halon owners make with respect to the disposition of agents from decommissioned systems.

In 2010 and 2015, banks of 31 and 24 ktonnes of Halon 1301, respectively and 33 and 19 ktonnes of Halon 1211, respectively, are projected to remain, but the emissions and the bank sizes will depend upon the effectiveness of practices to control leakage and to handle recovery at end-of-life. Banks of HFC/PFC/HCFC/FK in fixed systems at a 2% emission rate are projected to be 44 ktonnes in 2010 and 63 ktonnes in 2015, of which approximately 3.6 ktonnes consists of HCFCs. The portable extinguisher bank at a 4% emission rate is projected to be 3.0 ktonnes in 2010 and 3.9 ktonnes in 2015, assuming a 3% growth rate, of which it is estimated that approximately 68% are HCFCs, 30% are HFCs and 2% are PFCs. Looking to the future, GHG emissions from halocarbon-based clean agent systems may either increase or decrease depending on future market acceptance of the alternatives to halons. As research into new fire protection technologies continues, additional replacement options will likely emerge post-2015.

4.7 What are the most important findings for non-medical aerosols and solvents and for HFC-23 emissions?

What are past and current trends?

Prior to the Montreal Protocol, ODSs were widely used as a cleaning solvent for metals, electronics and precision applications, and in consumer and technical and safety aerosols as propellants or solvents. ODS use in these applications has been eliminated or reduced dramatically. Most solvent cleaning applications now rely on not-in-kind substitutes. A small percentage have or are expected to transition to HFCs or hydrofluoroethers (HFEs). PFC use is declining and expected to be eliminated by 2025.

Non-medical aerosols

Aerosol products use gas pressure to propel liquid, paste or powder active ingredients in precise spray patterns with controlled droplet size and quantity. They can also be made into products that use the gas only. In developed countries, 98% of non-medical aerosols now use non-ozone-depleting, very low GWP propellants (hydrocarbons, dimethylether, CO_2 or nitrogen). These substitutions led to a total reduction of GHG emissions from non-medical aerosol origin by over 99% between 1977 and 2001. The remaining aerosol products using either HCFCs (in developing countries where HCFC consumption is allowed until 2040) or HFCs (HFC-152a and HFC–134a) do so because these propellants provide a safety, functional or health benefit for the users. Additionally, the use of HFCs in non-medical aerosols is further limited by cost. HFCs are between five and eight times more expensive than hydrocarbons. In 2003, HFC use in aerosols represented total emissions of about 22 $MtCO_2$-eq.

Solvents

It is estimated that by 1999, 90% of the ODS solvent use had been reduced through conservation and substitution with not-in-kind technologies (no-clean flux, aqueous or semi-aqueous cleaning and hydrocarbon solvents). The remaining 10% of solvent use is shared by several organic solvent alternatives. The in-kind substitutes for CFC-113 and CFC-11 include HCFCs, PFCs, HFCs and HFEs. The only HCFC solvents currently used are HCFC-141b and HCFC-225ca/cb. Most HCFC-141b use is for foam blowing; solvent applications represented less than 10% of its global use in 2002. The use of HCFC-141b is banned in the EU and is rapidly declining in other developed countries. In developing countries, the use of HCFC-141b is still increasing, especially in China, India and Brazil, as economic growth rates are high. HCFC-225ca/cb use is directed to niche applications, and because of its ODP and phase-out schedule, it is being gradually replaced by HFC, HFE and not-in-kind alternatives.

Production byproducts and fugitives

Emissions of ODSs, HFCs and PFCs also occur during the production of fluorocarbons, either as undesired byproducts or as losses of useful material as fugitive emissions. Fugitive losses are small and generally represent less than 1% of total production. The most significant of the byproducts is HFC-23 (fluoroform), which is generated during the manufacture of HCFC-22. While the Montreal Protocol will eventually phase out the direct use of HCFC-22, its use as a feedstock is permitted to continue indefinitely because it does not involve the release of HCFC-22 to the atmosphere. Global feedstock demand has been increasing and is expected to continue to grow beyond 2015. HCFC-22 production is growing rapidly in developing countries, especially China and India. Commercial (non-feedstock) uses will end by 2020 in developed countries and by 2040 in developing countries.

HFC-23 generation ranges from 1.4–4% of total HCFC-22 production, depending on production management and process circumstances. HFC-23 is the most potent (GWP of 14,310) and persistent (atmospheric life 270 years) of the HFCs. Global emissions of HFC-23 increased by an estimated 12% between 1990 and 1995 as a result of a similar increase in the global production of HCFC-22. However, due to the widespread implementation of process optimization and thermal destruction in developed countries, this trend has not continued and since 1995 has become smaller than the increase in production.

Table TS-24. Overview of non-medical aerosol propellant alternatives.

	HCFC-22	HFC-134a	HFC-152a	Dimethylether	Isobutane[a]
Substance characteristics					
Radiative efficiency (W m^{-2} ppb^{-1})	0.20	0.16	0.09	0.02	0.0047
Atmospheric lifetime (yr)	12	14	1.4	0.015	0.019
GWP (100-yr time horizon)					
- This report	1780	1410	122	1	n/a
- IPCC (1996)	1500	1300	140	1	
ODP	0.05	~0	-	-	-
Ground-level ozone impact					
- MIR[2] (g-O1/g-substance)	<0.1	<0.1	<0.1	0.93	1.34
- POCP[3] (relative units)	0.1	0.1	1	17	31
Flammability (based on flashpoint)	None	None	Flammable	Flammable	Flammable
Technical data					
Stage of development	Commercial	Commercial	Commercial	Commercial	Commercial
Type of application:					
- Technical aerosols	X	X	X	X	X
- Safety aerosols	X	X			
- Consumer products	Phased out in industrialized countries		X	X	X
Emissions	Use totally emissive in all cases				
Costs					
Additional investment costs			Special safety required at filling plant	Special safety required at filling plant	Special safety required at filling plant

Notes:
[a] Listed values refer to isobutane only. Additional hydrocarbon aerosol propellants are used in non-medical aerosol applications as indicated in Chapter 10.

What emission reduction options are available?

<u>Non-medical aerosols</u>
Although there are no technical barriers for the transition out of CFCs to alternatives for non-medical aerosol products, in 2001, there was still an estimated 4300 tonnes of CFCs used in developing countries and countries with economies in transition (CEIT). Technical aerosols are pressurized gas products used to clean, maintain, fix, test, manufacture or disinfect various types of equipment or used in a number of processes. The largest use of HFCs in technical aerosols occurs in dusters where the substitution of HFC-134a by HFC-152a is a leading factor in reducing GHG emissions. For cleaners (contact cleaners, flux removers) and mould release agents, the substitution of HCFC-141b by HFEs and HFCs with lower GWP offers the opportunity for additional emission reduction with no substantial technical issues. Safety aerosols (safety signal horns, tire inflators) and insecticides for planes and restricted areas continue to rely on HFC-134a due to its non-flammability. Cosmetic, convenience and novelty aerosol products include artificial snow, silly string and noise-makers (horns). The majority of noise-makers (>80%) use hydrocarbons; artificial snow and string novelties originally transitioned to hydrocarbons but, after highly publicized safety incidents, were reformulated to HFC-134a. HFC use in cosmetic, convenience and novelty aerosols is being banned in the EU.

Table TS-24 presents a comparison of non-medical aerosol alternatives.

<u>Solvents</u>
Although HFCs are available in all regions, their use as solvents has been primarily in developed countries due to high costs and the concentration for applications in high-tech industries. With increasing concern about climate protection, HFC uses tend to be focused in critical applications with no other substitutes. Current use in developed countries is considered to have peaked and may even decline in the future.

PFC solvents are no longer considered technically necessary for most applications, and their use is constrained to a few

Table TS-25. Overview of HFCs, PFCs and HCFCs in solvent applications.

	HCFC-141b	HCFC-225ca/cb	HFC-43-10mee	HFC-365mfc	PFC–51-14 (C_6F_{14})
Substance characteristics					
Radiative efficiency (W m^{-2} ppb^{-1})	0.14	0.2/0.32	0.4	0.21	0.49
Atmospheric lifetime (yr)	9.3	1.9/5.8	15.9	8.6	3,200
GWP (100-yr time horizon)					
- This report	713	120/586	1,610	782	9,140
- IPCC (1996, 2001a)	600	180/620	1,300	890	7,400
ODP	0.12	0.02/0.03	-	-	-
Ground-level ozone impact					
- MIR (g-O_1/g-substance)	<0.1	<0.1	n/a	n/a	n/a
- POCP (relative units)	0.1	0.2/0.1	n/a	n/a	n/a
Ground-level ozone impact	None	None	None	None	None
Flammability (based on flashpoint)	None	None	None	Flammable	None
Technical data					
Stage of development	Commercial	Commercial	Commercial	Commercial	Commercial
Type of application:					
- Electronics cleaning	X	X	X		
- Precision cleaning	X	X	X	X	X
- Metal cleaning	X	X	X		
- Drying	X	X	X	X	
- Carrier solvent	X	X	X		X

niche applications due to very limited performance and high cost. Volumes are known to have decreased since the mid-1990s as a result of replacement with lower GWP solvents.

Emission reduction options in solvent applications fall into two categories:

(1) Improved containment in existing uses. New and retrofitted equipment can significantly reduce emissions of all solvents. Optimized equipment can reduce solvent consumption by as much as 80% in some applications. Due to their high cost and ease of recycling, the fluorinated solvents are generally recovered and reused by the end-users or their suppliers.

(2) Alternative fluids and technologies. A variety of organic solvents can replace HFCs, PFCs and ODSs in many applications. These alternative fluids include lower GWP compounds such as traditional chlorinated solvents, HFEs and n-propyl bromide. The numerous not-in-kind technologies, including hydrocarbon and oxygenated solvents, are also viable alternatives in some applications. Caution is warranted prior to adoption of any alternatives whose toxicity profile is not complete. In a limited number of applications, no substitutes are available due to the unique performance characteristics of the HFC or PFC in that case.

Tables TS-25 and TS-26 present comparisons of solvent alternatives.

Production byproducts and fugitives

It is technically feasible to reduce future emissions of HFC-23 from HCFC-22 by over 90% (or by a factor of ten) through capture and destruction of the HFC-23 byproduct. However, emissions of HFC-23 could grow by as much as 60% between now and 2015, from about 15 ktonnes yr^{-1} to 23 ktonnes yr^{-1} due to anticipated growth in HCFC-22 production. The upper bound of HFC-23 emissions is in the order of 3–4% of HCFC-22 production, but the actual quantity of HFC-23 produced depends in part on how the process is operated at each facility.

Techniques and procedures to reduce the generation of HFC-23 through process optimization can reduce average emissions to 2% or less of production. However, actual achievements vary for each facility, and it is not possible to eliminate HFC-23 emission by this means. Capture and destruction of HFC-23 by thermal oxidation is a highly effective option to reduce emissions. Destruction efficiency can be more than 99.0%, but the impact of 'down time' of thermal oxidation units on emissions needs to be taken into account. Assuming a technological lifetime of 15 years, specific abatement costs of less than 0.2 US\$/tCO_2-eq can be calculated.

Table TS-26. Overview of alternative fluids and not-in-kind technologies in solvent applications.

	CH_2Cl_2[a]	HFE-449s1[b]	n-propyl bromide	No Clean	Hydro-carbon / oxygenated	Aqueous / semi-aqueous
Substance characteristics						
Radiative efficiency (W m^{-2} ppb^{-1})	0.03	0.31	0.3	n.a.		n.a.
Atmospheric lifetime (yr)	0.38	5	0.04	n.a.		n.a.
GWP (100-yr time horizon)						
- This report	10	397	n/a	n.a.		n.a.
- IPCC (1996)	9	not given				
ODP	-	-	-	-	-	-
Ground-level ozone impact						
- MIR[3] (g-O_1/g-substance)	0.07	n.a.	n.a.			
- POCP[4] (relative units)	7	n.a.	n.a.			
Ground-level ozone impact	Low to moderate	None	Low to moderate	None	Low to moderate	None
Flammability (based on flashpoint)	None	None	None	n.a.	Flammable	n.a.
Technical data						
Stage of development	Commercial	Commercial	Commercial	Commercial	Commercial	Commercial
Type of application:						
- Electronics cleaning		X	X	X	X	X
- Precision cleaning		X	X		X	X
- Metal cleaning	X	X	X		X	X
- Drying					X	
- Carrier solvent	X	X	X		X	

Notes:

[a] The listed values refer to CH_2Cl_2 only. Additional chlorinated solvents are used in these applications as indicated in Chapter 10.

[b] The listed values refer to HFE-449s1 only. Additional HFE solvents are used in these applications as indicated in Chapter 10.

The calculation of HFC-23 emissions requires data not only on the quantities of HCFC-22 produced (the activity) and the rate of emission (which is influenced by process design and operating culture) but also on the extent to which emissions are abated. This has a particular influence on the uncertainty of HFC-23 estimates of future emissions.

Table TS-27 presents a comparison of the process optimization and thermal oxidation as reduction options for HFC-23 byproduct emissions.

What are possible future trends?

Non-medical aerosols

HFC emissions in non-medical aerosols are estimated at 23 $MtCO_2$-eq in 2010. Low growth is projected for this sector through to 2015. While there are no technical barriers to formulate consumer products without HFCs, the use of HFC-152a in some products such as hairspray and deodorants will increase in the USA due to the implementation of regulations to control ground level ozone formation from hydrocarbon emission. Current volatile organic compound (VOC) controls in Europe do not exempt HFCs because of the broad definition of VOC (boiling point <250°C under standard pressure/temperature conditions). No other VOC regulations identified elsewhere in the world restrict the use of hydrocarbons in non-medical aerosols.

Solvents

Most solvent uses are emissive in nature with a short inventory period of a few months to 2 years. Although used solvents can and are distilled and recycled on site, essentially all quantities sold are eventually emitted. The distinction between consumption and emission (i.e. banking) is not significant for these applications. Projected global emissions of HFCs and PFCs from solvent uses are 4.2 $MtCO_2$-eq in 2010 and 4.4 $MtCO_2$-eq in 2015. Emissions of PFCs are assumed to decline linearly until they are no longer used in solvent applications by 2025.

Table TS-27. Comparison of HFC-23 byproduct from HCFC-22 production reduction options: process optimization and thermal oxidation.

	HCFC-22	HFC-23		
Substance characteristics				
Radiative efficiency (W m^{-2} ppb^{-1})	0.20	0.19		
Atmospheric lifetime (yr)	12	270		
GWP (100-yr time horizon)				
- This report	1780	14,310		
- IPCC (1996)	1500	11,700		
ODP	0.05	~0		
Flammability	None	None		
HFC-23 emission reduction options		**No Optimization**	**Process Optimization**	**Thermal Oxidation**
Stage of development		Commercial	Commercial	Commercial
Direct emissions		3–4% HCFC-22 produced	2–3% HCFC-22 produced	<1% HCFC-22 produced
Additional costs		Reference	Dependent on process and market can range from marginal saving to significant penalty	US$ 2–8 million total installed capital costs, with US$ 189–350 thousand annual operating costs

<u>Byproduct emissions of HFC-23</u>
The quantity of HFC-23 produced (and that, potentially, may be emitted) is directly related to the production of HCFC-22 and, as a result, emission forecasts require a scenario for future HCFC-22 production volumes. These will depend on the consumption of HCFC-22 in developed countries, which is declining, and the consumption in developing countries and global demand for fluoropolymers feedstock, both of which are increasing.

Based on a BAU scenario that exactly follows the requirements of the Montreal Protocol, consumption and production of non-feedstock HCFC-22 will fall by a factor of ten by 2015 from the average level in 2000–2003 in developed countries. In the same countries, growth in the demand for fluoropolymer feedstock is projected to continue increasing linearly, leading to the feedstock demand for HCFC-22 doubling there by 2015. In developing countries, the production of HCFC-22 for both feedstock and non-feedstock uses has grown rapidly in recent years; over the period 1997–2001, production for commercial (or non-feedstock) uses grew linearly at 20 ktonnes yr^{-1} and feedstock use grew at 4.1 ktonnes yr^{-1}. Projected at these rates until 2015, the total global requirement for HCFC-22 would become about 730 ktonnes yr^{-1} – about 40% of which would be for feedstock – compared with a total of 470 ktonnes yr^{-1} in the year 2000. (Table TS-28).

In the BAU case to 2015, it has been assumed that emissions from existing capacity (in both developed and developing countries) will continue at 2% of HCFC-22 production and that new capacity (mainly in developing countries) will emit HFC-23 at a rate of 4%. Consequently, emissions of HFC-23 could grow by 60% between now and 2015 – from about 15 ktonnes yr^{-1} in 2003 to 23 ktonnes yr^{-1} (Table TS-28).

In a variation of this scenario, the current best-practice technology comprising capture and thermal oxidation of the 'vent gases' is progressively introduced into all facilities, commencing in 2005. Destruction technology is assumed to be 100% efficient and to operate for 90% of the on-line time of the HCFC-22 plant. Reduced emissions were calculated from the same activity (in the form of assumed future HCFC-

Table TS-28. Historical and future emissions of HFC-23.

Year	HCFC-22 Production scenario (kt)	HFC-23 BAU emissions (kt)	HFC-23 Current best practice emissions (kt)
1990	341	6.4	6.4
1995	385	7.3	7.3
2000	491	11.5	11.5
2005	550	15.2	13.8
2010	622	19.0	8.8
2015	707	23.2	2.3

22 production) as the BAU case. The difference between the two HFC-23 forecasts is therefore solely due to the extent to which destruction technology is deployed. The forecasts represent potential extreme cases, and future changes in activity will tend to increase the probability of one or the other.

Destruction of byproduct emissions of HFC-23 from HCFC-22 production has a reduction potential of up to 300 $MtCO_2$-eq per year by 2015 and specific costs below 0.2 US$/$tCO_2$-eq according to two European studies in 2000. Reduction of HCFC-22 production due to market forces or national policies, or improvements in facility design and construction also could reduce HFC-23 emissions. [10.4]

Annex I: Glossary of Terms

The definitions in this glossary refer to the use of the terms in the context of the Summary for Policymakers of the Special Report on Ozone and Climate.

Aerosol
A suspension of very fine solid or liquid particles in a gas. Aerosol is also used as a common name for a spray (or 'aerosol') can, in which a container is filled with a product and a propellant and is pressurized so as to release the product in a fine spray.

Banks
Banks are the total amount of substances contained in existing equipment, chemical stockpiles, foams and other products not yet released to the atmosphere.

Best Practice
For this Report, best practice is considered the lowest achievable value of halocarbon emission at a given date, using commercially proven technologies in the production, use, substitution, recovery and destruction of halocarbon or halocarbon-based products.

Blends/Mixtures (Refrigeration)
A mixture of two or more pure fluids. Blends are used to achieve properties that fit many refrigeration purposes. For example, a mixture of flammable and nonflammable components can result in a nonflammable blend. Blends can be divided into three categories: azeotropic, non-azeotropic and near-azeotropic blends.

Blowing Agent (Foams)
A gas, volatile liquid or chemical that generates gas during the foaming process. The gas creates bubbles or cells in the plastic structure of a foam.

Business-As-Usual (BAU) Scenario (2015, This Report)
A baseline scenario for the use of halocarbons and their alternatives, which assumes that all existing regulation and phase-out measures, including the Montreal Protocol and relevant national regulations, continue to 2015. The usual practices (including end-of-life recovery) and emission rates are kept unchanged up to 2015.

Carbon Dioxide (CO_2)
A naturally occurring gas which occurs as a byproduct of burning fossil fuels and biomass, as well as other industrial processes and land-use changes. It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance and is the reference gas against which other greenhouse gases are generally measured.

Chlorofluorocarbons (CFCs)
Halocarbons containing only chlorine, fluorine and carbon atoms. CFCs are both ozone-depleting substances (ODSs) and greenhouse gases.

Climate Change
Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.

Note that Article 1 of the Framework Convention on Climate Change (UNFCCC) defines 'climate change' as 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability, observed over comparable time periods'. The UNFCCC thus makes a distinction between 'climate change' attributable to human activities altering the atmospheric composition, and 'climate variability' attributable to natural causes.

Climate Variability
Variations in the mean state and other statistics (such as the standard deviation and the occurrence of extremes) of the climate on all temporal and spatial scales beyond that of individual weather events. Climate variability may be caused by natural internal processes within the climate system (internal variability), or by variations in natural or anthropogenic external forcings (external variability). See also: Climate change.

CO_2-Equivalent
The amount of carbon dioxide (CO_2) that would cause the same amount of radiative forcing as a given amount of another greenhouse gas. When used with concentrations this refers to the instantaneous radiative forcing caused by the greenhouse gas or the equivalent amount of CO_2. When used with emissions this refers to the time-integrated radiative forcing over a specified time horizon caused by the change in concentration produced by the emissions. See global warming potential.

Column Ozone
The total amount of ozone in a vertical column above the Earth's surface. Column ozone is measured in Dobson units (DU).

Containment (Refrigeration)
The application of service techniques or special equipment designed to preclude or reduce loss of refrigerant from equipment during installation, operation, service or disposal of refrigeration and air-conditioning equipment.

Destruction
Destruction of ozone-depleting substances (ODSs) by approved destruction plants, in order to avoid their emissions.

Dry Powder Inhaler (DPI) (Medical Aerosols)
An alternate technology to metered dose inhalers (MDIs) that can be used if the medication being dispensed can be satisfactorily formulated as microfine powder, thus eliminating the use of a chemical propellant.

Fluorocarbons
Halocarbons containing fluorine atoms, including chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

Fluoroketones (FKs)
Organic compounds in which two fully fluorinated alkyl groups are attached to a carbonyl group (C=O).

Global Warming Potential (GWP)
An index comparing the climate impact of an emission of a greenhouse gas relative to that of emitting the same amount of carbon dioxide. GWPs are determined as the ratio of the time-integrated radiative forcing arising from a pulse emission of 1 kg of a substance relative to that of 1 kg of carbon dioxide, over a fixed time horizon. See also: Radiative forcing.

Greenhouse Gases (GHGs)
The gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation within the spectrum of the thermal infrared radiation that is emitted by the Earth's surface, by the atmosphere and by clouds. This property causes the greenhouse effect. The primary greenhouse gases in the Earth's atmosphere are water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3). Moreover, there are a number of entirely anthropogenic greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances that are covered by the Montreal Protocol. Some other trace gases, such as sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs), are also greenhouse gases.

Halocarbons
Chemical compounds containing carbon atoms, and one or more atoms of the halogens chlorine (Cl), fluorine (F), bromine (Br) or iodine (I). *Fully halogenated halocarbons* contain only carbon and halogen atoms, whereas *partially halogenated halocarbons* also contain hydrogen (H) atoms. Halocarbons that release chlorine, bromine or iodine into the stratosphere cause ozone depletion. Halocarbons are also greenhouse gases. Halocarbons include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and halons.

Halons
Fully halogenated halocarbons that contain bromine and fluorine atoms.

Hydrocarbons (HCs)
Chemical compounds consisting of one or more carbon atoms surrounded only by hydrogen atoms.

Hydrochlorofluorocarbons (HCFCs)
Halocarbons containing only hydrogen, chlorine, fluorine and carbon atoms. Because HCFCs contain chlorine, they contribute to ozone depletion. They are also greenhouse gases.

Hydrofluorocarbons (HFCs)
Halocarbons containing only carbon, hydrogen and fluorine atoms. Because HFCs contain no chlorine, bromine or iodine, they do not deplete the ozone layer. Like other halocarbons they are potent greenhouse gases.

Hydrofluoroethers (HFEs)
Chemicals composed of hydrogen, fluorine and ether, which have similar performance characteristics to certain ozone-depleting substances (ODSs) that are used as solvents.

Life Cycle Assessment (LCA)
An assessment of the overall environmental impact of a product over its entire life cycle (manufacture, use and recycling or disposal).

Life Cycle Climate Performance (LCCP)
A measure of the overall global-warming impact of equipment based on the total related emissions of greenhouse gases over its entire life cycle. LCCP is an extension of the total equivalent warming impact (TEWI). LCCP also takes into account the direct fugitive emissions arising during manufacture, and the greenhouse gas emissions associated with their embodied energy.

Metered Dose Inhalers (MDIs) (Medical Aerosols)
A method of dispensing inhaled pulmonary drugs.

Miscible
The ability of two liquids or gases to uniformly dissolve into each other. Immiscible liquids will separate into two distinguishable layers.

Not-in-Kind Technologies (NIK)
Not-in-kind technologies achieve the same product objective without the use of halocarbons, typically with an alternative approach or unconventional technique. Examples include the use of stick or spray pump deodorants to replace CFC-12 aerosol deodorants; the use of mineral wool to replace CFC, HFC or HCFC insulating foam; and the use of dry powder inhalers (DPIs) to replace CFC or HFC metered dose inhalers (MDIs).

One-Component Foam (OCF)
A foam in which the blowing agent acts both as a frothing agent and as a propellant. These foams are primarily used for gap filling (to prevent air infiltration) rather than for thermal insulation per se. As such the use of blowing agent is fully emissive.

Ozone
The triatomic form of oxygen (O_3), which is a gaseous atmospheric constituent. In the troposphere it is created by photochemical reactions involving gases occurring naturally and resulting from anthropogenic activities ('smog'). Tropospheric ozone acts as a greenhouse gas. In the stratosphere ozone is created by the interaction between solar ultraviolet radiation and molecular oxygen (O_2). Stratospheric ozone plays a major role in the stratospheric radiative balance. Its concentration is highest in the ozone layer.

Ozone-Depleting Substances (ODSs)
Substances known to deplete the stratospheric ozone layer. The ODSs controlled under the Montreal Protocol and its Amendments are chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons, methyl bromide (CH_3Br), carbon tetrachloride (CCl_4), methyl chloroform (CH_3CCl_3), hydrobromofluorocarbons (HBFCs) and bromochloromethane.

Ozone Depletion
Accelerated chemical destruction of the stratospheric ozone layer by the presence of substances produced by human activities.

Perfluorocarbons (PFCs)
Synthetically produced halocarbons containing only carbon and fluorine atoms. They are characterized by extreme stability, non-flammability, low toxicity, zero ozone depleting potential and high global warming potential.

Radiative Forcing
Radiative forcing is the change in the net irradiance (expressed in Watts per square meter: $W\ m^{-2}$) at the tropopause due to an internal change or a change in the external forcing of the climate system, such as a change in the concentration of carbon dioxide (CO_2) in the atmosphere or in the output of the Sun. Usually radiative forcing is computed after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with all tropospheric properties held fixed at their unperturbed values. Radiative forcing is called *instantaneous* if no change in stratospheric temperature is accounted for. See also: Global warming potential.

Recovery
The collection and storage of controlled substances from machinery, equipment, containment vessels, etc., during servicing or prior to disposal without necessarily testing or processing it in any way.

Recycling
Reuse of a recovered controlled substance following a basic cleaning process such as filtering and drying. For refrigerants, recycling normally involves recharge back into equipment and it often occurs 'on-site'.

Refrigerant (Refrigeration)
A heat transfer agent, usually a liquid, used in equipment such as refrigerators, freezers and air conditioners.

Solvent
Any product (aqueous or organic) designed to clean a component or assembly by dissolving the contaminants present on its surface.

Specific Costs (of Abatement Options)
The difference in costs of an abatement option as compared with a reference case, expressed in relevant specific units. In this Report the specific costs of greenhouse gas emission reduction options are generally expressed in US$ per tonne of avoided CO_2-equivalents (US$/t$CO_2$-eq).

SRES Scenarios
Emission scenarios developed by the IPCC Special Report on Emission Scenarios (2000).

Stratosphere
The highly stratified region of the atmosphere above the troposphere. It extends from an altitude of about 8 km in high latitudes and 16 km in the tropics to an altitude of about 50 km. This region is characterized by increasing temperature with altitude.

Total Equivalent Warming Impact (TEWI)
A measure of the overall global-warming impact of equipment based on the total related emissions of greenhouse gases during the operation of the equipment and the disposal of the operating fluids at the end-of-life. TEWI takes into account both direct fugitive emissions, and indirect emissions produced through the energy consumed in operating the equipment. TEWI is measured in units of mass of CO_2 equivalent. See also: Life cycle climate performance (LCCP).

Troposphere
The lowest part of the atmosphere above the Earth's surface, where clouds and 'weather' phenomena occur. The thickness of the troposphere is on average 9 km in high latitudes, 10 km in mid-latitudes, and 16 km in the tropics. Temperatures in the troposphere generally decrease with height.

Annex II: Major Chemical Formulae and Nomenclature

This annex presents the formulae and nomenclature for several halogen-containing and other species that are referred to in the Summary for Policymakers.

The *Montreal Protocol on Substances that Deplete the Ozone Layer* controls the production and consumption of the following halocarbons: chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons, hydrobromofluorocarbons (HBFCs), carbon tetrachloride (CCl_4), methyl chloroform (CH_3CCl_3), methyl bromide (CH_3Br) and bromochloromethane (CH_2BrCl).

The *United Nations Framework Convention on Climate Change (UNFCCC)* covers anthropogenic emissions of greenhouse gases not controlled by the Montreal Protocol. The *Kyoto Protocol* of the UNFCCC covers the basket of greenhouse gases carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

Halocarbons

For each halocarbon the following information is given in columns:
- Chemical compound [Number of isomers if more than one] (or common name)
- Chemical formula
- Chemical name (or alternative name)

Chlorofluorocarbons (CFCs) [Production and consumption are controlled by the Montreal Protocol][1]

CFC-11		CCl_3F	Trichlorofluoromethane
CFC-12		CCl_2F_2	Dichlorodifluoromethane
CFC-13		$CClF_3$	Chlorotrifluoromethane
CFC-113	[2]	$C_2Cl_3F_3$	Trichlorotrifluoroethane
CFC-113		CCl_2FCClF_2	1,1,2-Trichloro-1,2,2-trifluoroethane
CFC-113a		CCl_3CF_3	1,1,1-Trichloro-2,2,2-trifluoroethane
CFC-114	[2]	$C_2Cl_2F_4$	Dichlorotetrafluoroethane
CFC-114		$CClF_2CClF_2$	1,2-Dichloro-1,1,2,2-tetrafluoroethane
CFC-114a		CCl_2FCF_3	1,1-Dichloro-1,2,2,2-tetrafluoroethane
CFC-115		$CClF_2CF_3$	Chloropentafluoroethane

---

[1] Note that the substances presented here are a selection of the substances that are controlled by the Montreal Protocol.

Hydrochlorofluorocarbons (HCFCs)

[Production and consumption are controlled by the Montreal Protocol][2]

HCFC-21	$CHCl_2F$	Dichlorofluoromethane
HCFC-22	$CHClF_2$	Chlorodifluoromethane
HCFC-123 [3]	$C_2HCl_2F_3$	Dichlorotrifluoroethane
HCFC-123	$CHCl_2CF_3$	2,2-Dichloro-1,1,1-trifluoroethane
HCFC-123a	$C_2HCl_2F_3$	1,2-Dichloro-1,1,2-trifluoroethane
HCFC-123b	$C_2HCl_2F_3$	1,1-Dichloro-1,2,2-trifluoroethane
HCFC-124 [2]		Chlorotetrafluoroethane
HCFC-124	$CHClFCF_3$	2-Chloro-1,1,1,2-tetrafluoroethane
HCFC-124a	C_2HClF_4	1-Chloro-1,1,2,2-tetrafluoroethane
HCFC-141b	CH_3CCl_2F	1,1-Dichloro-1-fluoroethane
HCFC-142b	CH_3CClF_2	1-Chloro-1,1-difluoroethane
HCFC-225ca	$CHCl_2CF_2CF_3$	3,3-Dichloro-1,1,1,2,2-pentafluoropropane
HCFC-225cb	$CHClFCF_2CClF_2$	1,3-Dichloro-1,1,2,2,3-pentafluoropropane

Halons

[Production and consumption are controlled by the Montreal Protocol][2]

Halon-1202	CBr_2F_2	Dibromodifluoromethane
Halon-1211	$CBrClF_2$	Bromochlorodifluoromethane (Chlorodifluorobromomethane), R-12B1
Halon-1301	$CBrF_3$	Bromotrifluoromethane, R-13B1
Halon-2402	$CBrF_2CBrF_2$	1,2-Dibromotetrafluoroethane (1,1,2,2-Tetrafluoro-1,2-dibromoethane, 1,2-Dibromo-1,1,2,2-tetrafluoroethane)

Other Halocarbons

[Production and consumption are controlled by the Montreal Protocol][2]

Carbon tetrachloride	CCl_4	Halon 104, R-10
Methyl chloroform	CH_3CCl_3	1,1,1-Trichloroethane
Methyl bromide	CH_3Br	Halon-1001, Bromomethane
Bromochloromethane	CH_2BrCl	Halon-1011

Hydrofluorocarbons (HFCs)

HFC-23		CHF_3	Trifluoromethane
HFC-32		CH_2F_2	Difluoromethane (Methylene fluoride)
HFC-41		CH_3F	Fluoromethane (Methyl fluoride)
HFC-125		CHF_2CF_3	Pentafluoroethane
HFC-134	[2]	$C_2H_2F_4$	Tetrafluoroethane
HFC-134		CHF_2CHF_2	1,1,2,2-Tetrafluoroethane
HFC-134a		CH_2FCF_3	1,1,1,2-Tetrafluoroethane
HFC-143	[2]	$C_2H_3F_3$	Trifluoroethane
HFC-143		CH_2FCHF_2	1,1,2-Trifluoroethane
HFC-143a		CH_3CF_3	1,1,1-Trifluoroethane
HFC-152	[2]	$C_2H_4F_2$	Difluoroethane
HFC-152		CH_2FCH_2F	1,2-Difluoroethane
HFC-152a		CHF_2CH_3	1,1-Difluoroethane
HFC-161		CH_3CH_2F	Monofluoroethane (Ethyl fluoride)
HFC-227	[2]	C_3HF_7	Heptafluoropropane
HFC-227ca		$CF_3CF_2CHF_2$	1,1,1,2,2,3,3-Heptafluoropropane
HFC-227ea		CF_3CHFCF_3	1,1,1,2,3,3,3-Heptafluoropropane
HFC-236	[4]	$C_3H_2F_6$	Hexafluoropropane
HFC-236ca		$CHF_2CF_2CHF_2$	1,1,2,2,3,3-Hexafluoropropane
HFC-236cb		$CH_2FCF_2CF_3$	1,1,1,2,2,3-Hexafluoropropane
HFC-236ea		CHF_2CHFCF_3	1,1,1,2,3,3-Hexafluoropropane
HFC-236fa		$CF_3CH_2CF_3$	1,1,1,3,3,3-Hexafluoropropane
HFC-245	[5]	$C_3H_3F_5$	Pentafluoropropane
e.g. HFC-245ca		$CH_2FCF_2CHF_2$	1,1,2,2,3-Pentafluoropropane
HFC-245fa		$CHF_2CH_2CF_3$	1,1,1,3,3-Pentafluoropropane
HFC-365mfc		$CH_3CF_2CH_2CF_3$	1,1,1,3,3-Pentafluorobutane
HFC-43-10mee		$CF_3CHFCHFCF_2CF_3$	1,1,1,2,2,3,4,5,5,5-Decafluoropentane (2H,3H-Perfluoropentane)
HFC-c-447ef			$c\text{-}C_5H_3F_7$ Heptafluorocyclopentane

Perfluorocarbons (PFCs)

PFC-14	CF_4	Tetrafluoromethane (Carbon tetrafluoride)
PFC-116	C_2F_6 (CF_3CF_3)	Perfluoroethane (Hexafluoroethane)
PFC-218	C_3F_8 ($CF_3CF_2CF_3$)	Perfluoropropane (Octafluoropropane)
PFC-318 or PFC-c318	$c\text{-}C_4F_8$ ($-(CF_2)_4-$)	Perfluorocyclobutane (Octafluorocyclobutane)
PFC-3-1-10	C_4F_{10}	Perfluorobutane
PFC-5-1-14	C_6F_{14}	Perfluorohexane
PFC-6-1-16	C_7F_{16}	Perfluoroheptane
PFC-7-1-18		C_8F_{18} Perfluorooctane

Fluorinated Ethers

HFE-449s1	$C_5H_3F_9O$	Methyl nonafluorobutyl ether
	$CF_3(CF_2)_3OCH_3$ $(CF_3)_2CFCF_2OCH_3$	Perfluoroisobutyl methyl ether
HFE-569sf2	$C_6H_5F_9O$	
	$CF_3(CF_2)_3OCF_2CF_3$	Ethyl perfluorobutyl ether
	$(CF_3)_2CFCF_2OCF_2CF_3$	Ethyl perfluoroisobutyl ether
HFE-347pcf2	$C_4H_3F_7O$ $(CF_3CH_2OCF_2CHF_2)$	1,1,2,2-Tetrafluoroethyl 2,2,2-trifluoroethyl ether

Other Halocarbons

Trifluoroacetic acid (TFA)	$C_2HF_3O_2$ (CF_3COOH)	Perfluoric acid

Non-Halogenated Hydrocarbons

Methane	CH_4	R-50
Ethane	C_2H_6 (CH_3CH_3)	R-170
Propane	C_3H_8 $(CH_3CH_2CH_3)$	R-290
Butane	C_4H_{10} $(CH_3CH_2CH_2CH_3)$	R-600, n-Butane
Isobutane	C_4H_{10} $((CH_3)_2CHCH_2)$	R-600a, i-Butane, 2-Methylpropane
Pentane	C_5H_{12} $(CH_3(CH_2)_3CH_3)$	R-601, n-Pentane
Isopentane	C_5H_{12} $((CH_3)_2CHCH_2CH_3)$	R-601a, i-Pentane, 2-Methylbutane

The Special Report “Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons” provides information relevant to decision-making in regard to safeguarding the ozone layer and the climate system — two global environmental issues involving complex scientific and technical considerations. It was produced by the Intergovernmental Panel on Climate Change (IPCC) and the Technology and Economic Assessment Panel (TEAP) of the Montreal Protocol following an invitation of the United Nations Framework Convention on Climate Change and the Montreal Protocol.

Scientific evidence linking chlorofluorocarbons (CFCs) and other ozone-depleting substances (ODSs) to global ozone depletion led to the initial control of chemicals under the 1987 Montreal Protocol and to amendments and adjustments in the 1990s that added additional ODSs, agreed to phase-outs, and accelerated those phase-outs. As various approaches to the phase-out of ODSs were developed it was realized that some actions taken to reduce future depletion of the ozone layer, in particular the introduction of HFCs and PFCs, could affect global warming. When the Kyoto Protocol was negotiated in 1997, countries had new incentives to take account of how choices among substitutes could affect the objectives of both Protocols.

The potential of each ODS substitute to influence the climate system depends not only on the physical and chemical properties of the substance itself, but also on the factors that influence its emission to the atmosphere, such as containment, recycling, destruction and energy efficiency in particular applications. In eleven chapters and supporting annexes, the report provides the scientific context required for consideration of choices among alternatives to ODSs; potential methodologies for assessing options; and technical issues relating to greenhouse gas (GHG) emission reduction opportunities for each of the sectors involved, including refrigeration, air conditioning, foams, aerosols, fire protection and solvents. The report also addresses the future availability of HFCs.

The Intergovernmental Panel on Climate Change (IPCC) was established jointly by the World Meteorological Organization and the United Nations Environment Programme (UNEP). The UNEP Technology and Economic Assessment Panel (TEAP) was established by the Parties to the Montreal Protocol. The Panels provide authoritative international assessments of scientific, technical and socio-economic information on climate change (IPCC), and of the status of technology to protect the stratospheric ozone layer (TEAP).

The full Special Report is published by Cambridge University Press (http://www.cambridge.org), and the digital version can be accessed via the website of the IPCC Secretariat (http://www.ipcc.ch) or obtained on CDRom from the IPCC Secretariat.This brochure contains the Summary for Policymakers and Technical Summary of the report.