



HFCs: A Critical Link in Protecting Climate and the Ozone Layer

A UNEP Synthesis Report



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Glossary

Article 5 Countries: Any party of the Montreal Protocol who is a developing country and whose annual per capita consumption of the controlled substances is below the limits set in Article 5 of the Protocol.

Atmospheric lifetime: Time it takes for 67% of a molecules to be removed from the atmosphere in the absence of emissions.

Atmospheric mixing ratio: The fractional composition of a chemical in the atmosphere relative to the sum of all air molecules in the atmosphere.

The mixing ratio of a chemical is the number of molecules of X in a unit volume divided by the number of air molecules in a unit volume. Mixing ratios are usually expressed as parts-per-million (ppm), parts-per-billion (ppb), or parts-per-trillion (ppt).

Carbon dioxide equivalent (CO₂eq): A simple way to place emissions of various climate change agents on a common footing to account for their effect on climate.

A quantity that describes, for a given mixture and amount of greenhouse gas, the amount of carbon dioxide that would have the same global warming ability, when measured over a specified timescale.

Chlorofluorocarbons (CFCs): Molecules containing carbon, fluorine, and chlorine. CFCs are the major ozone depleting substances already phased out by the Montreal Protocol. Many CFCs are potent greenhouse gases.

Drop-in alternatives: Substances that can be used in existing equipment with very little or no modification to the equipment. Drop-in replacements were used to quickly replace CFCs. Examples include use of HCFC-22 in air conditioners. Such replacements are also possible with some HFCs.

Global Warming Potential (GWP): A relative index that enables comparison of the climate effect of the emissions of various greenhouse gases (and other climate changing agents). Carbon dioxide, the greenhouse gas that causes

the greatest radiative forcing because of its overwhelming abundance, is chosen as the reference gas.

GWP is also defined as an index based on the radiative forcing of a pulsed injection of a unit mass of a given well-mixed greenhouse gas in the present-day atmosphere, integrated over a chosen time horizon, relative to the radiative forcing of carbon dioxide over the same time horizon. The GWPs represent the combined effect of the differing atmospheric lifetimes (i.e., how long these gases remain in the atmosphere) and their relative effectiveness in absorbing outgoing thermal infrared radiation. The Kyoto Protocol is based on GWPs from pulse emissions over a 100-year time frame.

20-year GWP: Global warming potential (see above) calculated for a time horizon of 20 years.

100-year GWP: Global warming potential (see above) calculated for a time horizon of 100 years.

GWP Weighting: A mathematical product of the emissions in tonnes and the GWP of a substance. GWP weighting is used routinely to evaluate the relative climate impact of emissions of various gases (by mass).

Hydrochlorofluorocarbons (HCFCs): Chemicals that contains hydrogen, fluorine, chlorine, and carbon. They do deplete the ozone layer, but have less potency compared to CFCs. Many HCFCs are potent greenhouse gases.

Hydrofluorocarbons (HFCs): Chemicals that contains hydrogen, fluorine, and carbon. They do not deplete the ozone layer and have been used as substitutes for CFCs and HCFCs. Many HFCs are potent greenhouse gases.

Indirect climate effects: A metric that accounts for climate effects caused by the use of a product, such as increased energy consumption.

Additional climate forcing due to the energy used, or saved, during the application or product lifetime, as well as the energy used to manufacture the product, and any ODSs or HFCs used. For example, insulating foam

products in buildings and appliances reduces energy consumption, whereas refrigeration and air-conditioning systems consume energy over their lifetimes. Analyses of the total potential climate impact of specific products can be estimated by life cycle climate performance (LCCP) or similar models that account for all direct and indirect contributions.

Indirect radiative forcing: A metric that accounts for effects on the climate system of a given agent as a result of changes induced in other climate forcing agents. For example, the climate effects of ozone layer depletion caused by ODSs.

In this report, indirect radiative forcing refers to the change in ozone radiative forcing due to the addition of ODSs. Stratospheric ozone losses are generally thought to cause a negative radiative forcing, cancelling part of the increased radiative forcing arising from the direct influence of the halocarbons. The magnitude of the indirect effect is strongly dependent on the altitude profile of the halogen-induced ozone loss and will vary depending on the source gas considered.

Intervention scenarios: A scenario where action is taken to change the amount of emissions of a given chemical.

Non-article 5 countries: Developed countries.

Not-in-kind alternatives: Products or technologies not using halocarbons. Not-in-kind alternative technologies achieve the same product objective without the use of halocarbons, typically by using 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).

Ozone depleting substances: Chemicals that can deplete the ozone layer. In this report, they are restricted to those listed by the Montreal Protocol in their annexes.

Ozone Depletion Potential (ODP): A measure of the extent of ozone layer depletion by a given ozone depleting substance, relative to that depleted by CFC-11. (CFC-11 has an ODP of 1.0).

There are many variants of ODPs. In this report, we use only the steady-state ODP, which is used by the Montreal Protocol. Steady-state ODP is defined by the time-integrated change of global ozone due to a unit mass emission of the ODS at the Earth's surface, relative to that from a similar emission of a unit mass of CFC-11.

Radiative Forcing: A measure of how a climate forcing agent influences the energy balance of Earth, with a positive value indicating a net heat gain to the lower atmosphere, which leads to a globally average surface temperature increase, and a negative value indicating a net heat loss.

Radiative forcing is the instantaneous change in the net, downward minus upward, irradiance (expressed in $W m^{-2}$) at the tropopause due to a change in an external driver of climate change, such as, a change in the concentration of a greenhouse gas (e.g., carbon dioxide), land use change, or the output of the Sun. Radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium.

Short-lived climate forcers: Substances (mainly chemicals) that influence climate but whose influence is quickly reduced once their emissions cease. These molecules are quickly removed from the atmosphere.

Stratospheric ozone: Ozone (O_3) present in the stratosphere located between roughly 15 and 45 km above Earth's surface.

Transitional substitute: Substitutes for CFCs, Halons, and few other ODSs that were introduced with the idea that their use would cease after more environmentally acceptable alternatives were found.

Acronyms

AC	Air-conditioning
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
CDM	Clean Development Mechanism
CFC	Chlorofluorocarbon
CO ₂	Carbon dioxide
FTOC	Foam Technical Options Committee of TEAP
GHG	Greenhouse gas
GTZ	Deutsche Gesellschaft fuer Technische Zusammenarbeit
GWP	Global Warming Potential (for specific time horizons)
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
IPCC	Intergovernmental Panel on Climate Change
LCCP	Life-Cycle Climate Performance
MAC	Mobile Air Conditioning
MCII	Multilateral Fund Climate Impact Indicator
MDI	Metered dose inhaler
MLF	Multilateral Fund for the implementation of the Montreal Protocol
ODP	Ozone Depletion Potential
ODS	Ozone depleting substance
RTOC	Refrigeration Technical Options Committee of TEAP
SAE	Society of Automotive Engineers International
SAP	Scientific Assessment Panel
TEAP	Technology and Economic Assessment Panel
TFA	Trifluoroacetic acid
UNEP	United Nations Environment Programme
UNFCCC	UN Framework Convention on Climate Change
US EPA	United States Environmental Protection Agency
WMO	World Meteorological Organization

Foreword



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The Montreal Protocol on Substances that Deplete the Ozone Layer has emerged as one of the truly outstanding success stories of international cooperation on sustainable development.

Since the 1980s, nations have worked together to phase-out the chemicals that have been damaging and degrading the ozone layer – the Earth’s protective shield that filters out harmful levels of ultra-violet light.

More recently science has spotlighted that this international effort has also spared humanity a significant level of climate change—perhaps buying back to date many-years-worth of greenhouse gas emissions or avoided annual emissions, between 1988 and 2010 equal to about 8 Gt of CO₂ equivalent.

This is because the original ozone-depleting substances, which the Montreal Protocol is phasing out, such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), are not only ozone-depleting but also serious climate-damaging gases.

The focus of this report is the opportunity for action on the latest replacement chemicals known as hydrofluorocarbons (HFCs).

HFCs are excellent substitutes for use in products such as refrigerators and industrial air conditioners, but they are extremely powerful global warming gases.

This report, *HFCs: A Critical Link in Protecting Climate and the Ozone Layer*, says that the current contribution to climate forcing by HFCs is less than one per cent. However, it warns that HFCs are rapidly increasing in the atmosphere as they are adopted as ozone-friendly alternatives. Emissions of HFCs are growing at a rate of 8% per year, and by 2050, without action, they could rise so high that they almost cancel the tremendous climate benefits won earlier by the phase-out of CFCs and other ozone-depleting substances.

This may challenge international efforts to keep a global temperature rise under 2 degrees C or less this century—the target agreed at the UN climate convention meeting in 2009 and reaffirmed in Cancun in 2010.

The good news, outlined in this report, is that alternatives exist that can assist in bringing down the projected growth in HFCs, if urgent action is taken.

There are diverse range of alternatives—from designing buildings that avoid the need for air conditioning to use of alternative substances such as hydrocarbons and ammonia, to use of HFCs with less global warming potential and shorter lifetimes than those of current concern.

The current gap between the ambition of nations and the scientific reality of where the world is heading with respect to climate change requires that all options are considered and all transformative actions pursued.

Action on the main greenhouse gases such as CO₂ and methane is at the core of that challenge. But action on other pollutants can also assist.

This scientific report underlines that HFCs need to be a clearer part of that landscape and brought more decisively into the suite of options for action that can assist in meeting and keeping the 2 degree C target.

Executive Summary

The Montreal Protocol has successfully protected the stratospheric ozone layer

The Protocol has been an effective instrument for protecting the Earth's stratospheric ozone layer by providing an international framework for phasing out ozone depleting substances (ODSs), including chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). The phase-out of ODSs has been accomplished by curtailing their production and consumption.

The phase-out of ODSs requires either substitute chemicals or other approaches, and hydrofluorocarbons (HFCs) have become the major replacements in many ODS applications (Figure ES 1). HFCs, which have no known natural sources, are used because they do not deplete the stratospheric ozone layer and can be used with relative ease (technically) in place of CFCs and HCFCs.

The Montreal Protocol has also effectively protected climate

Since most ODSs are also potent greenhouse gases, actions under the Montreal Protocol have had the very positive

side effect of substantially reducing a main source of global warming. Indeed, the phasing out of ODSs led to a drop between 1988 and 2010 of about 8.0 GtCO₂eq per year (gigatonnes equivalent CO₂ emissions) (Figure ES 2). The avoided annual emission of ODSs (approximately 10 Gt CO₂eq in 2010 alone) is about five times greater than the annual emissions reduction target for the first commitment period (2008–2012) of the Kyoto Protocol (UNEP 2011); it is one of the largest reductions to date in global greenhouse gas emissions.

The climate benefits of the Montreal Protocol may be offset by increases in HFCs

Like the ODSs they replace, many HFCs are potent greenhouse gases. Although their current contribution to climate forcing is less than 1% of all other greenhouse gases combined, HFCs have the potential to substantially influence climate in the future.

HFCs are rapidly increasing in the atmosphere as a result of their use as ODS replacements. For example, CO₂ equivalent emissions of HFCs (excluding HFC-23) increased by approximately 8% per year from 2004 to 2008.

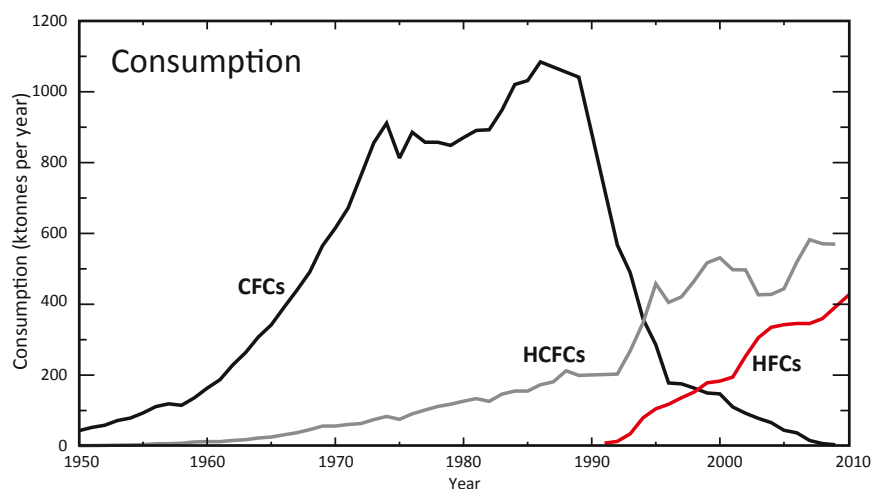


Figure ES 1. Global consumption (in kilotonnes per year) of ozone depleting CFCs and HCFCs. The phasing in of HFCs as replacements for CFCs is evident from the decrease in CFC usage concomitant with the increasing usage of HFCs. Use of HCFCs also increased with the decreasing use of CFCs. HCFCs are being replaced in part by HFCs as the 2007 Adjustment to the Montreal Protocol on HCFCs continues to be implemented. Thus, HFCs are increasing primarily because they are replacing CFCs and HCFCs.

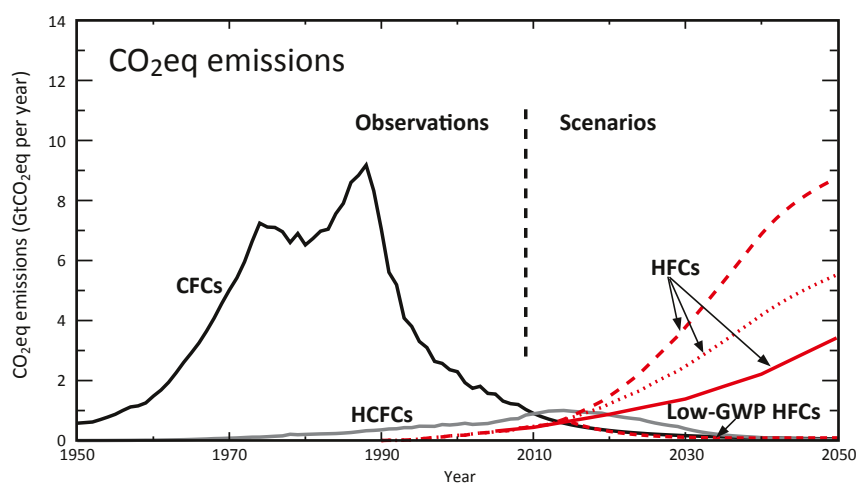


Figure ES 2. Trends in CO₂eq emissions of CFCs, HCFCs, and HFCs since 1950 and projected to 2050. The HFC emissions scenarios are from Velders et al. (2009) and Gschrey et al. (2011). The low-GWP HFC line represents the equivalent HFC emissions for a scenario where the current mix of emissions (with an average lifetime of HFCs of 15 years and an average GWP of 1600) was replaced by a mix of low GWP HFCs (with an average lifetime of less than 2 months or GWPs less than 20).

As a consequence, the abundances of HFCs in the atmosphere are also rapidly increasing (Figure ES 3). For example, HFC-134a, the most abundant HFC, has increased by about 10% per year from 2006 to 2010.

In the future, HFC emissions have the potential to become very large. Under current practices, the consumption of HFCs is projected to exceed by 2050 the peak consumption level of CFCs in the 1980s. This is primarily due to growing demand in emerging economies and increasing populations.

Without intervention, the increase in HFC emissions is projected to offset much of the climate benefit achieved by the earlier reduction in ODS emissions. Annual emissions of HFCs are projected to rise to about 3.5 to 8.8 Gt CO₂eq in 2050 which is comparable to the drop mentioned above in ODS annual emissions of 8.0 GtCO₂eq between 1988 and 2010.

To appreciate the significance of projected HFC emissions, they would be equivalent to 7 to 19% of the CO₂ emissions in 2050 based on the IPCC's Special Report on Emissions Scenarios (SRES), and equivalent to 18 to 45% of CO₂ emissions based on the IPCC's 450 ppm CO₂ emissions pathway scenario. There is, of course, inherent uncertainty in such projections.

If HFC emissions continue to increase, they are likely to have a noticeable influence on the climate system. By 2050, the buildup of HFCs is projected to increase radiative forcing by up to 0.4 W m⁻² relative to 2000 (Figure ES 4). This increase may be as much as one-fifth to one-quarter of the expected increase in radiative forcing due to the buildup of CO₂ since 2000, according to the SRES emission scenarios.

However, the future radiative forcing by HFCs in 2050 would be relatively small, at the same level as it is today (<1% of CO₂), if the current mix of HFCs were replaced with low-GWP substances with lifetimes of a few months or less.

There are options available to minimize the climate influence of HFCs

Alternative technical options for minimizing the influence of HFCs on climate fall into three categories:

- *Alternative methods and processes* (also called 'not-in-kind' alternatives): Commercially used examples include fibre insulation materials, dry-powder asthma inhalers and building designs that avoid the need for air-conditioners.
- *Using non-HFC substances with low or zero GWP*: Commercially used examples include hydrocarbons, ammonia, CO₂, dimethyl ether and other diverse substances used in various types of foam products, refrigeration, and fire protection systems.
- *Using low-GWP HFCs*: HFCs currently in use have a range of atmospheric lifetimes and GWPs (the shorter the lifetime, the lower the GWP). The mix of HFCs in current use, weighted by usage (tonnage), has an average lifetime of 15 years. However, several low-GWP HFCs (with lifetimes of less than a few months) are now being introduced, e.g. HFC-1234ze in foam products and HFC-1234yf for mobile air-conditioners.

A significant fraction of new equipment in some sectors already uses low-GWP alternatives (e.g., 36% of new domestic refrigerators and approximately 25% of new industrial air conditioners). However, low-GWP alternatives

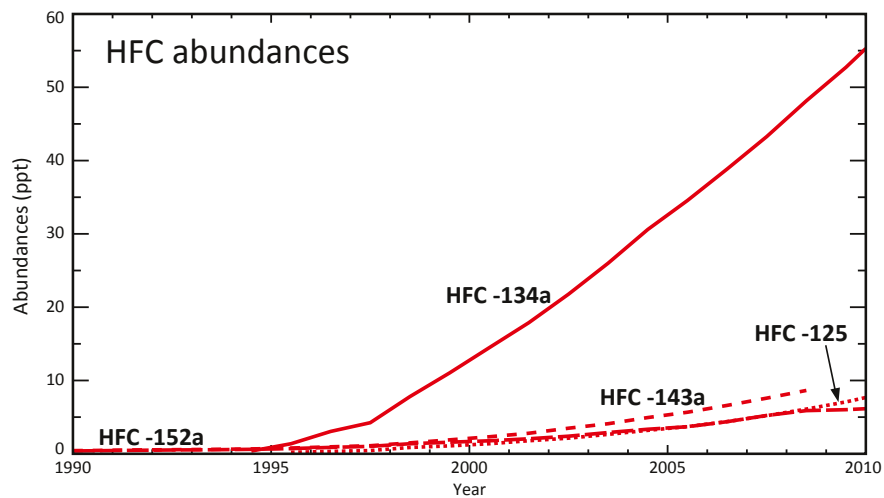


Figure ES 3. Global average atmospheric abundances of four major HFCs used as ODS replacements (HFC-134a, HFC-143a, HFC-125 and HFC-152a) since 1990. This illustrates the rapid growth in atmospheric abundances as a result of rapid increases in their emissions. These increases are attributed to their increased usage in place of CFCs and/or HCFCs. The increase in HFC-23, the second most abundant HFC in the atmosphere, are not shown since it is assumed that the majority of this chemical is produced as a byproduct of HCFC-22 and not because of its use as a replacement for CFCs and HCFCs. The abundance of HFC-23 was 22 ppt in 2008, with an annual growth rate of 0.83 ppt (roughly 4% per year) in that year.

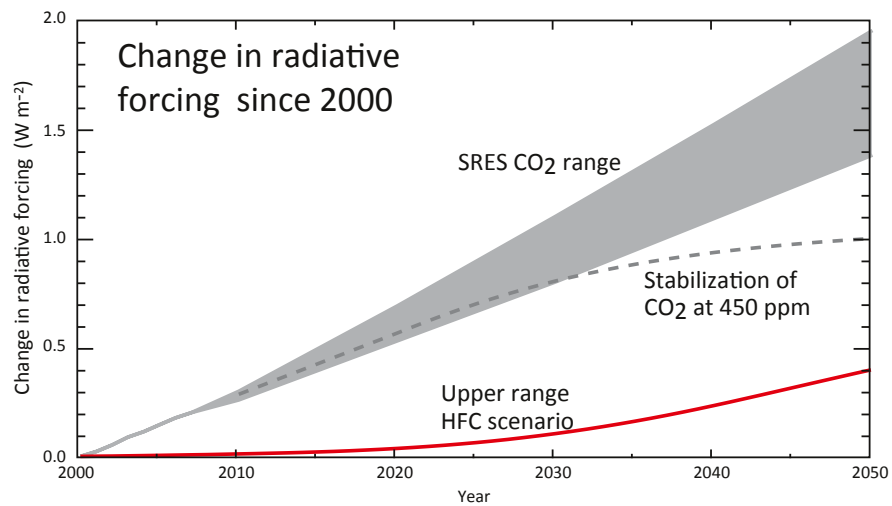


Figure ES 4. Projected radiative forcing of climate by HFCs and CO₂ since 2000, when the influence of HFCs was essentially zero. The HFC climate forcing for an upper range scenario is compared with the CO₂ forcing for the range of scenarios from IPCC-SRES and the 450 ppm CO₂ stabilization scenario. Clearly, the contribution of HFCs to radiative forcing could be very significant in the future; by 2050, it could be as much as a quarter of that due to CO₂ increases since 2000, if the upper range HFC scenario is compared to the median of the SRES scenario. Alternatively, the contribution of HFCs to radiative forcing could be one-fifth of the radiative forcing due to CO₂ increases since 2000, if the upper range HFC scenario is compared to the upper range of the SRES scenario. The contribution of HFCs to radiative forcing could also be as much as 40% of the radiative forcing by CO₂ under the 450 ppm stabilization scenario.

only make up a small fraction of other sectors at present, although they have the potential to substantially increase their market share.

While there is some concern that replacing HFCs may lead to lower energy efficiency, recent studies have shown that a number of systems using low-GWP substances have equal or better energy efficiency than systems using high-GWP HFCs.

It is not unusual that barriers stand in the way of changes in technology, and this is also the case for alternatives to high-GWP HFCs. These barriers include: the need for further technical developments, risks due to flammability and toxicity, regulations and standards that inhibit the use of alternatives, insufficient supply of components, investment costs, and lack of relevant skills among technicians.

But the current use of alternatives to high-GWP HFCs demonstrates that these barriers can be overcome by activities such as, research and technological improvements, revised technical standards, training and technical assistance, as well as infrastructure developments.

While various alternative options are being evaluated or further developed, there are also some known measures that can be implemented to reduce emissions of HFCs. For example, the design of equipment can be modified to reduce leakage and the quantity of HFC used, and technical procedures can be modified to reduce emissions during manufacture, use, servicing and disposal of equipment.

As a general conclusion about HFC alternatives, it can be said that there is no 'one-size-fits-all' solution. The solution that works best will depend on many factors such as the local situation for production and use, the costs of different alternatives, the availability of components, and the feasibility of implementation.

Going Forward

To sum up, although replacing ozone depleting substances with HFCs helps to protect the ozone layer, increasing use and consequently emissions of high-GWP HFCs are likely to undermine the very significant climate benefits achieved by ODS phase-out.

It is still possible to maintain these climate benefits because ozone-friendly and climate-friendly alternatives exist for high-GWP HFCs in a number of sectors. But further work needs to be done before full advantage of these alternatives can be taken. It is important, for example, to update estimates of the climate influence of HFC scenarios; to further analyze technical and regulatory barriers, and how to overcome them; and to examine the 'life-cycle' impacts of various options to ensure that they do not have unacceptable side effects on society or the environment.

By pursuing this and other work, sustainable options for protecting both the ozone layer and the global climate are likely to be found.

Chapter 1:

Montreal Protocol and ozone layer protection

The Montreal Protocol has led to great progress in phasing out important ozone depleting substances, including CFCs, HCFCs, halons, and a number of other chemicals containing chlorine and bromine.

The Protocol is working as intended and expected. The depletion of the stratospheric ozone layer has been curtailed and the ozone layer is expected to recover to its 1980 levels during this century.

But a particular side effect of implementing the Protocol merits attention. As a result of phasing out ozone depleting substances, HFCs have been introduced as replacements in many applications and are now finding their way to the atmosphere.

HFCs vary significantly in their ability to influence climate; whereas some have low GWPs of less than 20, others are potent greenhouse gases with GWPs of thousands to tens-of-thousands. Given the fact that the GWP of the current mix of HFCs is about 1600, there is concern that HFCs could significantly influence climate in the future if they continue to increase.

The Montreal Protocol is an example of how countries can cooperate to successfully combat a serious global environmental problem. The actions agreed upon under the Protocol have led to a timely phase-out of ozone depleting substances and there is already evidence that the presence of these substances is decreasing in the atmosphere.

But one of the side effects of the phase-out has been the introduction of hydrofluorocarbons (HFCs) as a replacement for ozone-damaging chemicals in many applications. While HFCs do not deplete the ozone layer, many are potent greenhouse gases. Hence, HFCs represent a crucial link between protecting the ozone layer and protecting climate.

The purpose of this UNEP report is to provide a brief synthesis of existing knowledge about HFCs, in particular the links between climate change, ozone depleting substances and HFCs. The authors draw on previous reports by international bodies including: the IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System; the WMO/UNEP Scientific Assessment Panel reports; WMO/UNEP Synthesis reports; UNEP/TEAP reports; and other UNEP reports, as well as peer-reviewed publications that have emerged since the publication of these reports. This chapter reviews the benefits of the Montreal Protocol as a mechanism for protecting the ozone layer. Chapter 2 reviews the climate benefits of the phase-out of ozone depleting substances; Chapter 3 discusses the contribution of HFCs to climate forcing, now and under different future scenarios; and Chapter 4 examines the alternatives to high-GWP HFCs.

1. 1 The Montreal Protocol has successfully protected the ozone layer

Chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons, and other ozone depleting substances (ODSs) are recognized as the main cause of the observed depletion of the ozone layer and of the ozone hole (WMO 2011). The 1985 Vienna Convention for the Protection of the Ozone Layer and the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer formally recognized the significant threat that ODSs posed to the ozone layer and human health, as well as other potential effects, such as changes in climate.

Moreover, the Protocol and its subsequent Amendments and Adjustments provided mechanisms for the reduction and phase-out of production and consumption of ODSs. This was a major task because ODSs were once used in large quantities for refrigeration, air-conditioning, fire extinguishing, and as solvents, propellants, fumigants, and foam blowing agents. But the Protocol, together with national regulations and actions by companies and consumers, was successful in substantially decreasing the production, consumption and emissions of ODSs. The observed atmospheric concentrations of most CFCs, halons, methyl chloroform and several other ODSs, are indeed decreasing as expected from the Protocol and scientific understanding of the workings of the atmosphere (Figure 1.1) (WMO 2011).

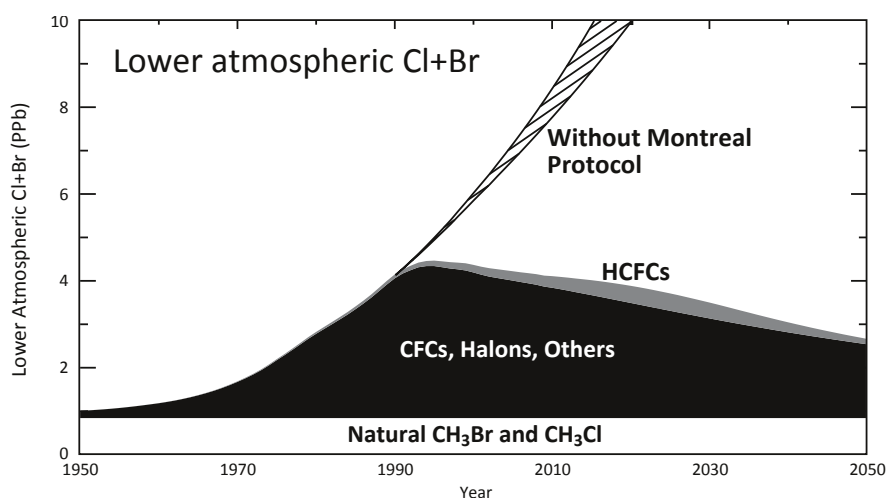


Figure 1.1. Change in lower atmospheric abundance (in parts per billion, ppb) of the sum of chlorine and bromine arising from ODSs as a result of the Montreal Protocol. The bromine abundance has been multiplied by a factor of 60 to account for the 60-times higher efficiency of bromine, relative to chlorine, (on a per-atom basis) in depleting the stratospheric ozone layer. The hatched region is an estimate of the atmospheric abundance of chlorine plus bromine that would have occurred without the Montreal Protocol, assuming a 2–3% increase in annual production of all ODSs (Figure based on Velders et al., 2007)

1.2 The Montreal Protocol is gradually phasing out ODSs

Under the provisions of the Montreal Protocol and its Amendments and Adjustments, CFCs were scheduled to be phased out in developed (non-Article 5) Countries/Parties by 1996 and in developing (Article 5) Countries/Parties by 2010, with small allowances for special exempted uses. The first phase of the CFC phase-out utilized both ‘not-in-kind alternatives’ (products or technologies that can substitute for applications that require ODSs) and ‘drop-in replacements’ (chemicals that can be used in existing equipment with very little or no modifications to the equipment); the latter were mostly HCFCs and HFCs. HCFCs have Ozone Depletion Potentials (ODPs) that are 10–50 times smaller than CFCs and were classified under the Protocol as ‘transitional substitutes’ to be used during the time it took to commercialize new ozone-safe alternatives and replacements (Figure 1.2). HFCs have essentially zero ODPs and are considered to be ‘safe’ for the ozone layer.

In developed countries, the transition from using CFCs to HCFCs started in the 1980s and was completed by around 2000. The transition from CFCs and/or HCFCs to HFCs started in the 1990s and is now well underway. This has led to increased consumption (Figure 1.3) and, as will be seen in Chapter 3, increased emissions of HFCs. Developing countries completed their CFC phase-out in 2010, in accordance with the provisions of the Montreal Protocol.

The use of HCFCs has increased sharply in developing countries in the past decade, partly because they have substituted for CFCs in some applications, but also as a result of increased demand for products made with, or containing, HCFCs. This increased use of HCFCs resulted in an increase in their emissions, which is reflected in their atmospheric abundances (see Section 3.1).

In response to continued concerns about the ozone layer and increasing concerns about the global climate, the Parties to the Montreal Protocol decided in 2007 to accelerate HCFC phase-out. HCFC production and consumption in Article 5 Parties (developing countries) are scheduled to be frozen in 2013, followed by stepwise reductions, with a virtually complete phase-out by 2030. Non-Article 5 Parties (developed countries) have agreed to a near complete phase-out by 2020, with some countries aiming for an earlier date. Thus, it is expected that almost all HCFC production and consumption for emissive uses, i.e., uses where the substance can escape into the atmosphere, will cease by 2030.¹ In specifying the accelerated HCFC phase-out, Decision XIX/6 of the Montreal Protocol encouraged Parties to ‘promote the selection of alternatives to HCFCs that minimize environmental impacts; in particular impacts on climate, as well as meeting other health, safety and economic considerations.’ It is likely that this phase-out of HCFCs will use HFCs, at least to some degree.

1. With the exception of feedstock, process agents and other uses exempted under the Montreal Protocol

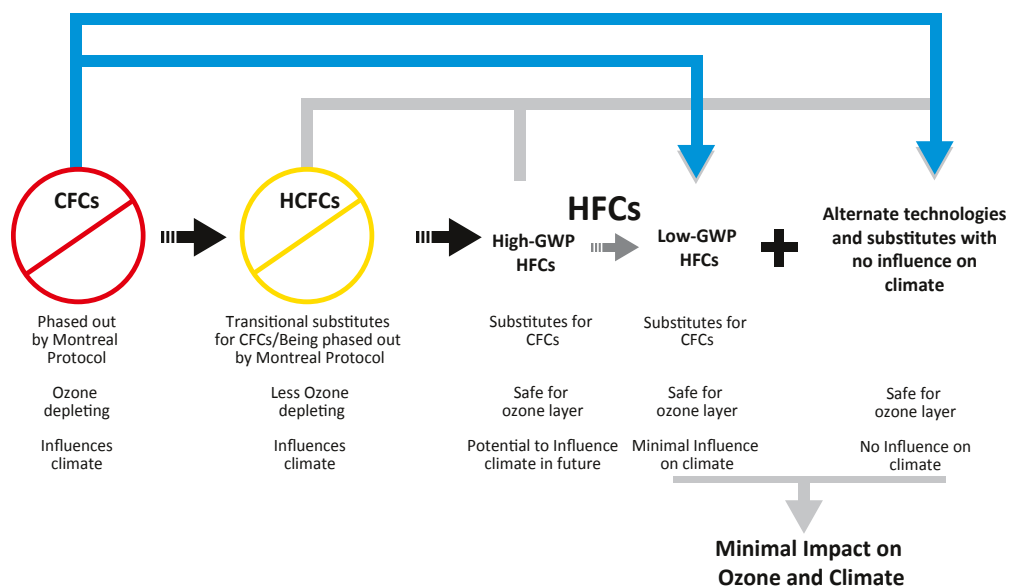


Figure 1.2. Flow diagram of ODS phase-out process. The first stage involved the utilization of HCFCs (which are less potent ozone depleting substances) as ‘drop-in replacements’ for CFCs, and also encouraged the use of ‘not-in-kind alternative chemicals and technologies’ (see glossary). Subsequent stages included replacing CFCs and HCFCs with other chemicals such as HFCs, with the eventual aim of developing chemicals and technologies that are ozone-layer-safe and also benign to climate. The potential benefits of replacing high-HFCs are discussed in this report.

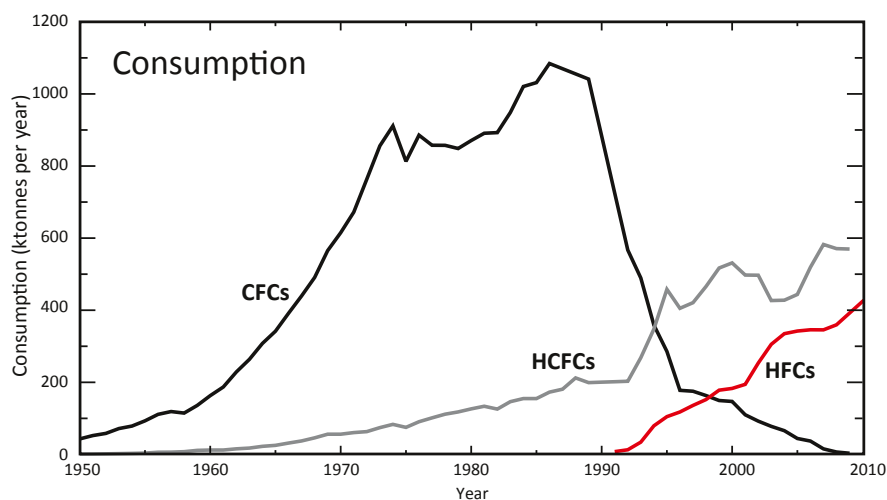


Figure 1.3. The transition in global consumption (by mass, in kilotonnes per year), from CFCs to HCFCs and to HFCs, their non-ozone depleting substitutes. The data for CFCs and HCFCs is based on consumption reported to UNEP. The HFC data is from Velders et al (2009) and is based on emissions derived from observed atmospheric abundances and reported production data from the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS). It is evident that the increase in HFC usage is concomitant with the decrease in CFC consumption.

1.3 The Montreal Protocol is working as expected and intended

The global emissions of CFCs and many other ODSs peaked in the late 1980s and have decreased ever since. The corresponding abundances of most ODSs in the atmosphere peaked slightly later in the 1990s or 2000s (as expected) and have since decreased. In 2010, total ODS emissions, weighted by their ODPs, were about 25% of the peak in the 1980s. Without the Montreal Protocol, ODS emissions would have continued to increase from their peak in 1988 and could have almost doubled by 2010.

There is emerging evidence that the stratospheric ozone layer is responding to these changes in ODSs and beginning to recover to its 1980 state. Current knowledge suggests that the ozone layer will return to its 1980 levels towards the middle of the 21st century and that the ozone hole will disappear later in the 21st century. It is clear that adopting the Montreal Protocol has avoided large, and possibly catastrophic, damage to the ozone layer (WMO 2011).

In summary, the Montreal Protocol has avoided a:

- Continued increase in ODS emissions;
- Continued build up of ODSs in the atmosphere;
- Continued depletion of the ozone layer and an expanding ozone hole.

This success was accomplished by using not-in-kind chemicals and technologies, as well as substitutes that were much less potent ozone depleting substances. The utilization of HFCs has contributed to the success of the Montreal Protocol.

1.4 HFCs are substitutes for ODSs

HFCs² have been introduced into commercial use largely because they have proven to be effective substitutes for ODSs. They do not deplete the ozone layer and are suitable for use in applications where CFCs and HCFCs were used. These chemicals have no known natural sources. Thus, HFCs are present in the atmosphere because they were used to comply with the provisions of the Montreal Protocol.

HFCs have found widespread use in various applications. They are used in refrigeration and air-conditioning equipment in homes, other buildings and industrial operations (~55% of total HFC use in 2010, expressed in CO₂eq) and for air-conditioning in vehicles (~24%). Smaller amounts are used for foam products (~11%), aerosols (~5%), fire protection systems (~4%) and solvents (~1%) (Figure 1.4). The use of HFCs is increasing rapidly as a result of global economic development and population growth.

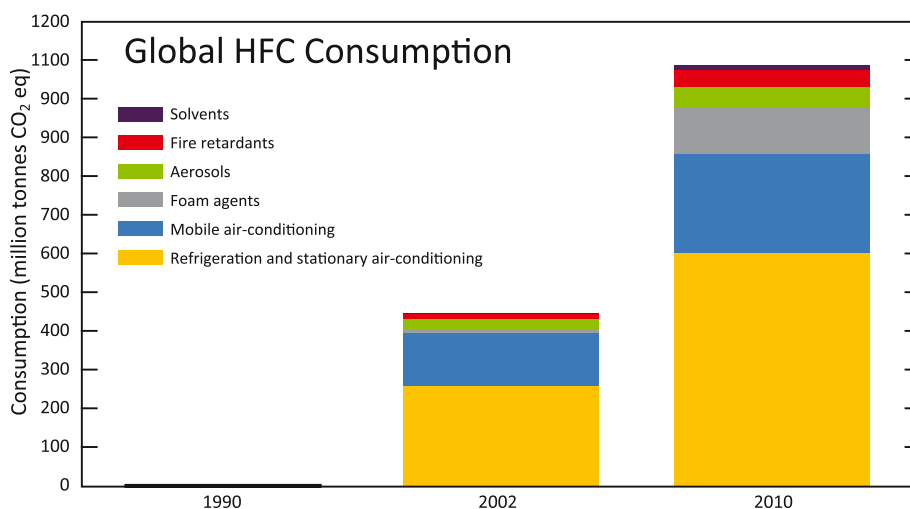


Figure 1.4. Estimated global consumption of HFCs by various sectors, expressed in CO₂ equivalent, for 1990, 2002 and 2010 (TEAP 2005, EPA 2010a). HFCs are predominantly used for the same industrial uses as the CFCs and HCFCs which are subject to phase-out under the Montreal Protocol. The rapid growth in HFCs after 1990 is also clearly evident.

The published estimates used in this figure are significantly higher (after accounting for the difference in units) than those shown in Figure ES 1 and Figure 1.3. The differences arise because of the ways in which CO₂ equivalent consumption is calculated and because of the differences in data sets used. We used different data here in order to provide a time series for the sectoral breakdown. This sectoral information was not available for the data in Figure ES 1 and Figure 1.3.

2. The synthesis in this report covers all HFCs apart from HFC-23. See Box 1 for further information.

1.5 Many HFCs are potent greenhouse gases

HFCs are greenhouse gases that trap infrared radiation in the atmosphere that would otherwise escape to space. The abilities of all HFCs to absorb infrared is roughly similar to that of CFCs and HCFCs, and is much greater than those of CO₂, methane, or nitrous oxide, on a per-molecule or per-mass basis. However, HFCs vary significantly in their ability to influence climate. Their differing ability is mostly due to differences in their atmospheric lifetimes, which determine how much they accumulate in the atmosphere. HFCs with lifetimes greater than a few years accumulate more in the atmosphere (for the same annual emission) and have larger climate consequences, while those with shorter lifetimes

do not accumulate as much, and have less influence on the climate. HFCs with lifetimes of several years have large Global Warming Potentials (GWPs)³. For example, HFC-134a, with an atmospheric lifetime of approximately 13 years, has a GWP of 1370. In contrast, HFCs with very short lifetimes (days to weeks) have low GWPs. For example, HFC-1234yf has a lifetime of approximately 10 days and is estimated to have a GWP of 4. Clearly, HFCs are not all the same when it comes to their ability to influence climate.

Of concern, is the fact that the average GWP of the current mix of HFCs being used is about 1600⁴, meaning that a kg of currently used HFC has about 1600 times the effect on global warming as a kg of CO₂.

Box 1. HFC-23 and its role in forcing climate

HFC-23 is an important greenhouse gas. It is mostly generated as a by-product during the manufacture of HCFC-22. It is not included in this report, because this report focuses on HFCs that are produced and used primarily as ODS substitutes. The charts and projections presented in this report are based on studies that estimate future HFC emissions by extrapolating existing trends in the use of HFCs as ODS substitutes. Hence, HFC-23 cannot be included in the projections, as its emissions would rely on a completely different set of assumptions.

Nevertheless here is some background information about HFC-23:

- HFC-23 does not destroy stratospheric ozone.
- There is very little reported direct use of HFC-23. It has limited industrial uses, including use in semiconductor fabrication, very low temperature refrigeration and in specialty fire suppressant systems (Miller et al. 2010).
- HFC-23 is a very potent greenhouse gas with a 100-year GWP of 14,200 and an atmospheric lifetime of 222 years. This makes it one of the most potent greenhouse gases.
- HFC-23 is the second most abundant HFC in the atmosphere after HFC-134a, reaching about 22 ppt in 2009. Currently, HFC-23 contributes 25% to the climate forcing by HFCs (WMO 2011).
- It is estimated that the HFC-23 could contribute an annual emission up to 0.35 Gt CO₂ eq by 2035 that would lead to a radiative forcing up to 0.01 W m⁻² by that time (Miller and Kuijpers 2011). An alternative estimate suggests that, if HFC-23 were to continue to be produced as a by-product of HCFC-22 until 2050, the annual emission could be 0.25 Gt CO₂ eq (Gschrey et al. 2010)

- Currently, the release of HFC-23 to the atmosphere in some developed countries is restricted by national regulations, voluntary actions, and market incentives. Some HCFC-22 production facilities in developing countries capture and destroy HFC-23 (financed by carbon emission reduction credits under the Kyoto Protocol Clean Development Mechanism (CDM)). HFC-23 captured in CDM projects is destroyed by incineration.
- The atmospheric abundance of HFC-23 has increased over the past decade, as HCFC-22 production has increased (Montzka et al. 2010). These increases are likely due to the production of HCFC-22 in facilities that are not covered by the Kyoto Protocol's CDM projects. The increase in HFC-23 has not been proportional to the production of HCFC-22 since the implementation of the CDM projects reduced the HFC-23 releases. The globally averaged abundance is increasing at a rate of about 4% per year.
- Although HCFC-22 production is controlled for refrigerant and other end uses and is scheduled for phase-out by 2040, its production as a feedstock for the manufacture of other chemicals is not controlled under the Montreal Protocol. (Montzka et al. 2010). Therefore, the unintended emission of HFC-23 as a byproduct of HCFC-22 production is expected to continue beyond 2040 unless restricted by international, national, or voluntary actions (Miller and Kuijpers 2011). The future levels are, therefore, difficult to estimate, and appropriate projections are not currently available.

3. GWP weighting is used routinely to evaluate the relative climate impact of emissions of various gases (by mass) and is the basis for greenhouse gas emission targets under the Kyoto Protocol, which uses the 100-year GWP. In this report, we will also use the 100-year GWP. See Glossary for further explanation.

4. This value is calculated using the amounts used, weighted by their GWP, for the various components of the current mix of HFCs (Based on Velders et al. (2009)).

Chapter 2:

Climate benefits of the Montreal Protocol

Since most ODSs are potent greenhouse gases, actions under the Montreal Protocol have had the positive effect of reducing a main source of global warming.

The ODS phase-out has resulted in one of the largest reductions to date in global greenhouse gas emissions.

2.1 Actions under the Montreal Protocol have reduced and avoided emissions of important greenhouse gases

It has been known since the pioneering work of Ramanathan (1975) that ODSs are greenhouse gases, which contribute to the radiative forcing of climate. As a consequence, the phase-out of ODSs, under the Montreal Protocol, has had the added benefit of protecting the global climate.

The effects of ODS emissions on climate can be evaluated using two metrics: CO₂equivalent (CO₂eq) emissions, based on the GWP-weighting of the emissions; and the radiative forcing that is governed by the atmospheric abundances of ODSs (IPCC/TEAP 2005; Velders et al. 2007; WMO 2011). Using these metrics, ODS emissions can be compared with anthropogenic CO₂ emissions, derived from observations and future scenarios.

Although ODS emissions are much smaller than CO₂ emissions, several ODSs significantly influence climate because they are potent greenhouse gases with high GWPs. The 100-year GWPs of the principal ODSs, range between 5 (methyl bromide) and 11,000 (CFC-12), which is clearly much larger than that of CO₂ (GWP of CO₂ is defined to be 1).

The annual contribution of ODSs to equivalent CO₂ emissions, inferred from atmospheric observations, peaked in 1988 at 9.4 Gt CO₂eq per year, a value slightly less than half of global annual CO₂ emissions at that time (Velders et al. 2007; Figure 2.1). After 1988, the equivalent CO₂ emissions of ODSs fell sharply, in contrast to increasing CO₂ emissions. By 2010, ODS emissions had declined by around 8.0 Gt CO₂eq per year to 1.4 Gt CO₂eq per year (Figure 2.1), or about 5% of CO₂ emissions for that year. Without the Montreal Protocol, the ODS emissions could have reached 15–18 Gt CO₂eq per year in 2010, about half the CO₂ emissions that year (Velders et al. 2007). This is about 11–13 times larger than their current level.

2.2 Actions under the Montreal Protocol have reduced radiative forcing by ODSs

The contribution of ODSs to radiative forcing, and hence climate change, depends on the accumulation of emitted ODSs in the atmosphere. Furthermore, the effect on the climate system depends not only on the radiative forcing by the chemical of interest, but also on how that chemical alters atmospheric abundances of other climate gases (indirect climate effects). The radiative forcing from ODSs reached a value of 0.32 W m⁻² around 2000 and remain more or less constant since. At the same time, from 2003 to 2010, radiative forcing values for CO₂ increased by 0.2 W m⁻².

Without the Montreal Protocol, the projected radiative forcing by ODSs would have been roughly 0.65 W m⁻² in 2010 (Velders et al. 2007). This would have been 35% of the current forcing by CO₂ of 1.8 W m⁻², and would have made the contribution of ODSs, collectively, to radiative forcing second only to CO₂. The radiative forcing avoided by reducing ODS emissions amounts to about 0.3 W m⁻² in 2010. To understand the importance of this figure, this avoidance is about one-fifth of the radiative forcing caused by the increase of CO₂ in the atmosphere since the pre-industrial era.

2.3 Some of the climate benefits of the Montreal Protocol have been offset

The direct climate benefits of the Montreal Protocol, discussed above, have been partially offset by several factors:

First, when ozone-depleting substances are reduced, the ozone layer recovers, and as a result, the level of ozone in the upper atmosphere increases. Since ozone is also a greenhouse gas, this recovery adds to the global

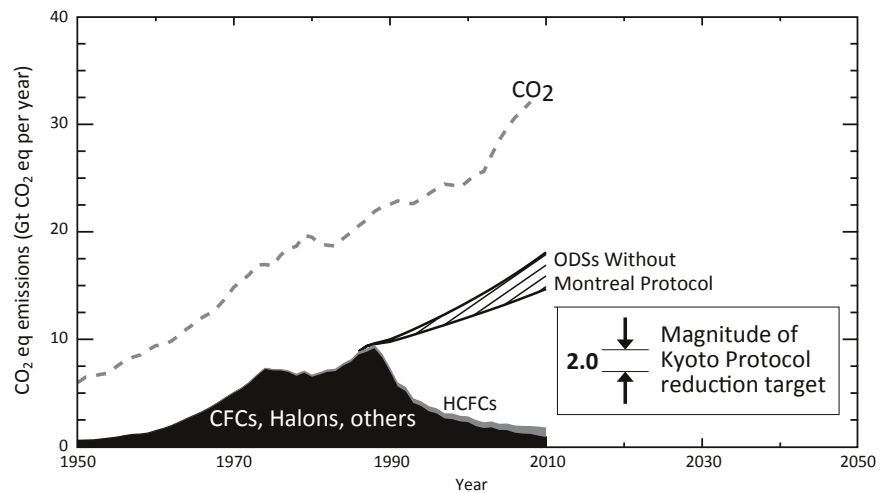


Figure 2.1. Climate benefits of the Montreal Protocol expressed by the decrease in CO₂eq emissions of ODSs (CFCs, halons, HCFCs, and others). The hatched regions show that, without the Montreal Protocol, CFC and other ODS emissions would have continued to increase greatly after 2010. The box in the diagram also shows that the target for reducing emissions under the Kyoto Protocol from 1990 to 2010 was about 2 Gt CO₂eq per year, but emissions from ODSs dropped by about 8 Gt CO₂eq per year during the same period. By 2010, the level of ODS emissions was small relative to CO₂ emissions (from energy and industry). Figure adapted from Velders et al. (2007).

greenhouse effect. This process is estimated to offset the direct climate benefits of ODS reductions by about 20%⁵.

Second, replacing ODSs with HFCs, many of which are potent greenhouse gases, has led to an increase in radiative forcing from HFCs (see Chapter 3). This effect is estimated to offset the climate benefits of the Montreal Protocol to date by up to 10%.

These two factors combined have offset the direct climate benefits of the Montreal Protocol by up to 30% (Velders et al. 2007).

In addition, the phasing out of ODSs has led to various 'life cycle' changes in technologies and the operation of technologies. These changes have not been quantified in all applications, but some of these changes are likely to have had an indirect effect on emissions of greenhouse gases (see Section 3.7). For example, refrigeration equipment that used CFCs has been replaced in some cases by more energy efficient equipment with reduced total emissions of greenhouse gases, and in other cases by less energy efficient equipment, which may increase emissions.

2.4 The climate benefits of the Montreal Protocol are greater than the Kyoto target

The phase-out of ODSs under the Montreal Protocol avoided an estimated 10 Gt CO₂eq per year emissions in 2010, taking into account the ODS emissions that could have occurred in the absence of the Montreal Protocol, the offsets by ozone depletion and increases in HFC emissions. This figure for 2010 is about five times greater than the annual emissions reduction target for the first commitment period (2008–2012) of the Kyoto Protocol, estimated⁶ at 2 Gt CO₂eq per year (see Figure 2.1) (UNEP 2011) and is one of the largest reductions to date in greenhouse gas emissions. Thus, it is clear that the Montreal Protocol has already contributed significantly to limiting the radiative forcing of Earth's climate.

As noted earlier, HFCs that replaced CFCs or HCFCs are also influencing climate. Currently, the contribution to climate forcing by HFCs is small, but it is expected to increase greatly in the future, as will be discussed in Chapter 3. It is precisely this projected increase that has focused attention on HFCs.

5. That is, the reduction of ODS emissions has avoided a radiative forcing of about 0.3 W m⁻² in 2010 (see text). But the recovery of the ozone layer has been estimated to have increased radiative forcing by around 0.05 ± 0.10 W m⁻² (IPCC, 2007), or about 20% of 0.3 W m⁻².

6. The adopted CO₂ equivalent emissions reduction target for the first commitment period of the Kyoto Protocol is -5.8%, corresponding to -0.97 Gt CO₂eq per year by 2008–2012. Because most countries would normally have had increasing greenhouse gas emissions after 1990, the emission reduction necessary to achieve the agreed Kyoto target has been calculated from a business-as-usual scenario between the 1990 baseline and 2008–2012. Business-as-usual projections from UNFCCC have total greenhouse gas emissions of Annex-1 parties increasing by 6% (1.06 Gt CO₂eq per year) above the 1990 value by 2010 in the absence of the Kyoto Protocol. Therefore, an arguably more realistic estimate of the greenhouse gas emission reduction achieved by meeting the first Kyoto Protocol target is the combination of the 5.8% decrease and 6% increase for a total of about 2 Gt CO₂eq per year.

Chapter 3:

HFCs and climate change

HFC emissions and their atmospheric abundances are rapidly increasing.

Without intervention, HFC emissions in the future (say by 2050) could offset much of the climate benefit achieved by the Montreal Protocol.

HFCs vary in 'strength' with regard to their influence on climate. Some have short lifetimes (less than a few months) and low GWPs, and some have long lifetimes (from several to tens of years) and high GWPs.

3.1 The atmospheric abundances of HFCs are increasing rapidly

Atmospheric observations⁷ show that the abundance of HFCs in the atmosphere is increasing rapidly (Figure 3.1):

- HFC-134a increased by about 10% per year from 2006 to 2010, reaching 58 ppt in 2010. HFC-134a, used in mobile air conditioning and many other applications, has become the most abundant HFC in the atmosphere;
- HFC-125, used in refrigeration and air conditioning, increased by more than 15% per year from 2006 to 2010, reaching 8 ppt in 2010;
- HFC-143a, used in refrigeration and air conditioning, increased by about 15% per year from 2004 to 2008, reaching 9 ppt in 2008.

Atmospheric observations of other high-GWP HFCs, (e.g., HFC-32, -152a, -365mfc, 245fa, -236fa and -227ea), have been reported to be increasing; although, their rate of increase was ≤ 1 ppt/yr in 2008 (WMO 2011). The rate of atmospheric increase depends on both the emission amount and the atmospheric lifetime of the HFCs.

3.2 Equivalent CO₂ emissions of HFCs are still small compared to other emissions but are increasing rapidly

The emissions of high-GWP HFCs, as inferred from observed atmospheric abundances, are increasing very rapidly at about 10-15% per year (Figure 3.1). These increases translate into equivalent CO₂ emissions of HFCs

(excluding HFC-23) of 8-9% per year from 2004 to 2008 (WMO 2011). However, the sum of HFC emissions in 2008 (0.39 ± 0.03 Gt CO₂eq per year; weighted by direct, 100-year GWPs) is still small compared to emissions of other greenhouse gases such as CFCs (1.1 ± 0.3 Gt CO₂eq per year); HCFCs (0.74 ± 0.05 Gt CO₂eq per year); N₂O (~ 3 Gt CO₂eq per year); CH₄ (~ 9 Gt CO₂eq per year), and CO₂ (from fossil fuel combustion, ~ 31 Gt CO₂eq per year) (WMO 2011).

The recent growth in emissions of HFCs at 8-9% per year is notably greater than the recent increases of about 4% per year in the case of CO₂ and about 0.5% per year in the case of methane.

The Parties to the Montreal Protocol do not report the production and consumption of HFCs to the UN. However, developed (Annex 1) countries do report HFC emissions data to the UN Framework Convention on Climate Change. But the reported emissions cannot be compared directly with the global emissions in Figure 3.1 because they are only a subset of total global emissions.

3.3 The current contribution of HFCs to climate forcing is small but rapidly growing

The current contribution of HFCs to direct climate forcing is calculated to be approximately 0.012 W m^{-2} . Thus, the contribution from HFCs to date has been less than 1% of the total climate forcing by other greenhouse gases. However, the annual increase in HFC forcing in the past few years is significant when compared to that of other substances during the same period. During a 5-year period,

7. Independent air sampling networks collect air at different locations around the globe with a range of sampling frequencies; they provide consistent results for a range of trace gases, including HFCs (WMO, 2011).

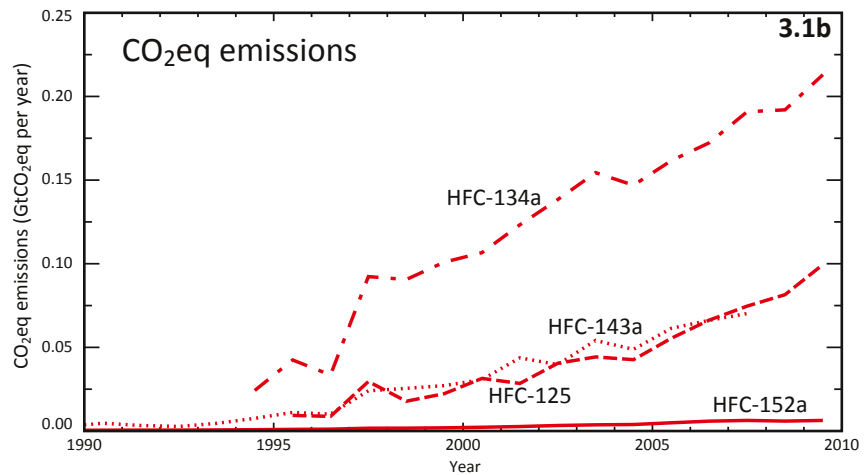
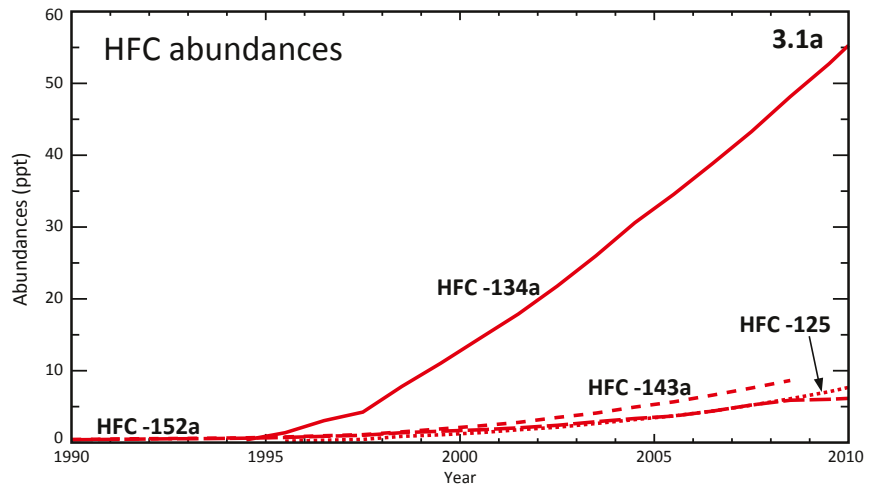


Figure 3.1 Increase in global average observed atmospheric abundances (3.1a) in parts per trillion, ppt and global annual CO₂eq emissions per year (3.1b) of four major HFCs. The emissions are inferred from the observed abundances. Not shown is HFC-23, the second most abundant HFC in the atmosphere with an abundance of about 22 ppt in 2009 (See Box 1). (Observed abundances from Chapter 1 of WMO (2011) with updates from Advanced Global Atmospheric Gases Experiment (AGAGE) data).

from mid 2003 to mid 2008, total radiative forcing from HFCs increased by about 0.006 W m^{-2} , which was slightly lower than the increase from HCFCs (0.008 W m^{-2}), half of the increase from N_2O (0.012 W m^{-2}), and larger than the increase from methane (0.004 W m^{-2}). These increases in radiative forcing from HFCs can be compared to the decrease of 0.008 W m^{-2} from other ODSs (mainly CFCs) over the same period. However, they are still relatively small compared to the increase from CO_2 (0.14 W m^{-2}) over this same period. The major concern with respect to HFCs is not that they are currently large climate forcing agents, but that their contribution to climate forcing is expected to increase rapidly in the future, such that they could become very significant contributors under some scenarios. HFC emissions scenarios and their implications for climate forcing are discussed in the next section.

3.4 Different types of future HFC emissions scenarios have been constructed

Scenarios have been developed and published by various authors to assess the potential impact of future HFC emissions on climate. They can be broadly divided into non-intervention and intervention scenarios.

Non-intervention scenarios

Non-intervention scenarios provide projected emissions up to at least the middle of the 21st century (usually 2050). They extrapolate historical and current technological developments, and assume no targeted policy intervention to reduce emissions. They are guided mainly by assumptions about economic and population growth. The projections of future HFC emissions and abundances summarized in this report are based on non-intervention scenarios developed by Velders et al. (2009) and Gschrey et al. (2011):

- Velders et al. (2009) developed four scenarios based on assumptions similar to those of IPCC-SRES (IPCC 2000). With respect to growth rates in gross domestic product (GDP) and population, but incorporated new information about: (i) HCFC consumption in developing countries, and (ii) the replacement of HCFCs by HFCs in developed countries. The scenarios have upper and lower ranges that reflect the range in IPCC-SRES scenarios for growth in GDP and population.
- Gschrey et al. (2011) based their scenario on sector-specific growth rates and emissions factors for all relevant sectors in developed and developing countries.

Both the Velders et al. (2009) and Gschrey et al. (2011) scenarios take into account the accelerated phase-out schedules of HCFCs and the EU Mobile Air Conditioning Directive (EC 2006). The scenarios differ in their

assumptions about growth rates in major HFC-consuming sectors. The upper range scenario of Velders et al. (2009) is based on the growth rates in the IPCC-SRES A1 scenario and the lower range scenario of the A2 scenario, while the Gschrey et al. (2011) scenario is based on a combination of the IPCC-SRES A1 and B1 scenarios. The growth rates in the latter scenario are therefore slightly lower than in the upper range scenario of Velders et al. (2009). The scenarios also differ in projected market saturation effects after about 2030, and different replacement patterns for ODSs by HFCs and not-in-kind alternatives.

Intervention scenarios

Intervention scenarios are based on assumptions of future potential policies and measures to control emissions. The discussions by the Parties to the Montreal Protocol to promote the use of HCFC alternatives that minimize the influence on climate are also considered to be an intervention.

- An HFC intervention scenario was developed for IPCC/TEAP (2005) and recently updated (TEAP 2009a), covering up to 2015 and 2020, respectively. Because of the short time periods covered by these scenarios, they are not shown in Figures 3.2 and 3.3.
- The new scenarios constructed for IPCC, the Representative Concentration Pathways (RCPs), also contain HFC emissions, but are based on an older analysis of HFC growth. They also do not account for the accelerated phase-out of HCFCs, nor the latest growth in demand for HCFCs and HFCs. Therefore, these scenarios, as for those of IPCC-SRES, are not included in this report.

Hence, the figures and data presented in this report have used information only from recent non-intervention scenarios.

3.5 HFC emissions have the potential to become very large and at least partly offset the climate benefits of the Montreal Protocol

Emissions of HFCs are projected to continue increasing under all non-intervention scenarios (WMO 2011) and to exceed the 1988-peak in ODS emissions (in tonnes, but not equivalent CO_2) by 2050. It is important to note that there is inadequate knowledge about current trends in emissions to determine which scenario will be more likely.

Figure 3.2 shows equivalent CO_2 emissions of HFCs up to 2050, according to the scenarios of Velders et al. (2009) and Gschrey et al. (2011). By 2050, the total HFC emissions are 5.5–8.8 Gt CO_2eq per year under the Velders et al. (2009) set of scenarios and 3.5 Gt CO_2eq per year under the Gschrey et al. (2011) scenario. HFC emissions clearly

have the potential to become very large. Emissions of HFCs are projected to exceed those of ODSs after about 2020 (Figure 3.2) due primarily to growing demand in emerging economies and increasing populations.

As noted in Chapter 2, actions under the Montreal Protocol led to a drop of ODS emissions between 1988 and 2010 equivalent to about 8.0 Gt CO₂eq per year. Without intervention, the increase in HFC emissions projected by both Velders and Gschrey will offset much of this climate benefit (Figure 3.2).

The projected HFC emissions can also be put into context by comparing them to projected global CO₂ emissions in 2050. HFC emissions (on a CO₂ equivalent basis) calculated from data in Gschrey et al. (2011) are about 7% of global CO₂ emissions in 2050 (not shown) and HFC emissions projected by Velders et al. (2009) are about 9-19% of these CO₂ emissions. Compared to the lower level of CO₂ emissions expected in 2050 (not shown); under a scenario of CO₂ stabilization at 450 ppm (IPCC 2007), these figures are 18%, and 28-45%, respectively (Figure 3.2). Hence, future HFC emissions may also be substantial when compared to future levels of CO₂ emissions.

3.6 The radiative forcing of HFCs is also projected to significantly increase

The current contribution of HFCs to radiative forcing is relatively small, at about 0.012 W m⁻². But by 2050, it could be ten to thirty times larger. Velders et al. (2009) estimate an increase to 0.25–0.40 W m⁻². The authors of this report calculate a radiative forcing of 0.10-0.20 W m⁻² due to HFC emissions for the Gschrey scenario.⁸ The upper range value of 0.4 W m⁻² is about one-quarter of the expected increase in radiative forcing due to the buildup of CO₂ from 2000 to 2050 according to the IPCC-SRES scenarios (Figure.3.3); and 50-130% of the expected increase in forcing from other Kyoto greenhouse gases. In a further comparison, the HFC radiative forcing in 2050 (not shown) of 0.25-0.40 W m⁻² corresponds to 7–12% of the CO₂ values. This projected HFC radiative forcing in 2050 is therefore equivalent to 6–13 years of radiative forcing growth due to CO₂ in the 2050 time frame.

The increase in HFC radiative forcing from 2000 to 2050 can also be compared to the radiative forcing corresponding to a 450 ppm CO₂ stabilization scenario. The reduction in

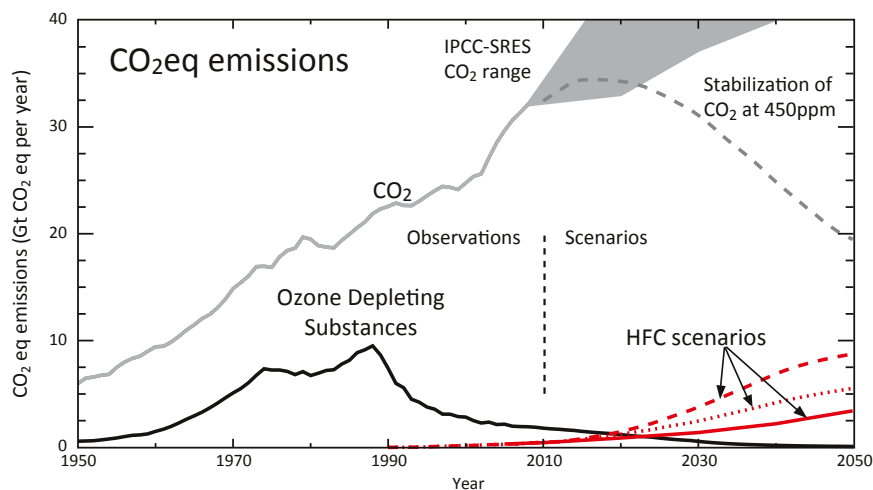


Figure 3.2. The decrease in CO₂ equivalent emissions of ODSs (CFCs, halons, HCFCs, and others) (line designated as ozone depleting substances) may be offset by the projected increase in their non-ozone depleting substitutes (HFCs) (lines designated as HFC scenarios). The HFC scenarios shown are the upper and lower (broken and dotted lines respectively) scenarios of Velders et al. (2009) and the scenario (solid line) of Gschrey et al. (2011). Shown for reference are emissions for the range of global CO₂ emissions from the IPCC-SRES scenarios (IPCC 2000; 2001) (grey shaded area), and for a 450 ppm CO₂ stabilization scenario (IPCC 2007) (grey broken line) (The CO₂ emissions depicted for 1950–2007 are reported emissions from fossil fuel use and cement production). The HFC intervention scenario from TEAP (2009a) only covers the period up to 2020, and is not shown because it would not be visible. The emissions of the TEAP (2009a) scenario are 0.8 Gt CO₂eq per year in 2020; about equal to the Gschrey et al. (2011) scenario and slightly below the Velders et al. (2009) scenarios. (Figure based on WMO 2011).

8. The radiative forcing was calculated using data from Gschrey et al. (2011).

radiative forcing necessary to go from a business-as-usual scenario (as in IPCC-SRES, Figure 3.3) to such a stabilization scenario is of the same order of magnitude as the increase in HFC radiative forcing. In other words, the benefits of going from a business-as-usual pathway to a pathway in which CO₂ stabilizes at 450 ppm can be counteracted by projected increases in HFC emissions.

There is, of course, inherent uncertainty in all projections about future levels of HFCs.

3.7 HFC emissions also have indirect climate effects

In the preceding scenarios, only the direct contribution to climate forcing due to HFC and ODS emissions is considered. But as noted in Section 2.3, the use of HFCs and halocarbons may have secondary effects on climate forcing. For example, thermal insulating products in buildings and appliances reduce energy consumption and thereby tend to reduce emissions, whereas refrigeration and air-conditioning systems consume energy over their lifetimes and may tend to increase emissions. A full evaluation of the total climate forcing (both direct and indirect), resulting from the global transition away from CFCs and HCFCs toward HFCs, would require consideration of lifecycle CO₂ emissions of all associated halocarbon, non-halocarbon, and not-in-kind alternatives (IPCC/TEAP 2005). A comprehensive and detailed evaluation of this kind has not been carried out to date.

3.8 Different HFCs have different atmospheric lifetimes and vary in their ability to influence climate

It is important to note that not all HFCs have the same influence on climate. As a group of gases, their influence varies significantly (see section 1.5). Their relative influence on climate is mostly due to differences in their atmospheric lifetimes, which determine how much they accumulate in the atmosphere. In general, the shorter the lifetime, the lower the accumulation in the atmosphere (for the same annual emission), and the lower the GWP. HFCs with shorter lifetimes will also be removed more quickly from the atmosphere, which means that their influence on climate will also diminish quickly once emissions cease.

Conversely, the longer the atmospheric lifetime, the bigger is their influence on climate. Fully saturated HFCs (for example, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a) have lifetimes ranging from 1 to 50 years (WMO 2011). Accordingly, their GWP for a 100-year time horizon also ranges greatly from 100 to 5,000 (Table 3.1). Unsaturated HFCs (also referred to as hydrofluoro-olefins, HFOs) have shorter atmospheric lifetimes in the order of days to weeks. Consequently their GWPs (100-year) are around 20 or less.

At present, a few low-GWP HFCs (with lifetimes less than a few months) are being either phased in or proposed as substitutes for HCFCs and some of the high-GWP HFCs

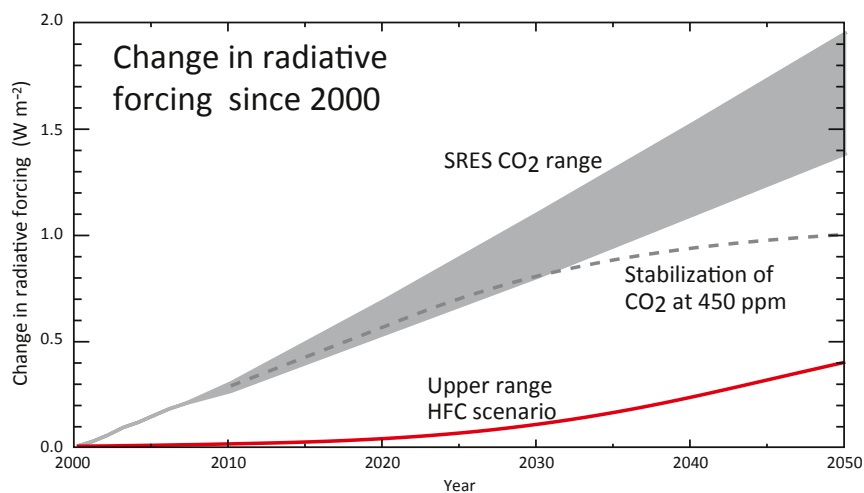


Figure 3.3. Projected increase in radiative forcing of HFCs. The increase is significant when compared to the increase in radiative forcing from CO₂ since 2000. For HFCs the upper range scenario of Velders et al. (2009) is shown. The change in radiative forcing for CO₂ is from the IPCC-SRES scenarios and for a 450 ppm CO₂ stabilization scenario (IPCC 2007). Data were not available for a radiative forcing calculation for the Gschrey et al. (2011) scenario, but the radiative forcing from this scenario is estimated to be 0.1 to 0.2 W m⁻² in 2050. (Figure based on Velders et al. 2009).

(with lifetimes from several to tens of years). Examples include: HFC-1234yf as a substitute for the refrigerant HFC-134a; HFC-161 as substitute for the refrigerant HCFC-22; and trans-HFC-1234ze as a substitute blowing agent for some thermal insulating foams (see Chapter 4). Some of

these low-GWP HFCs are so short-lived that the concept of GWP may not be applicable to them (WMO 2011).⁹ For the purpose of comparison, they are estimated to be a hundred to a thousand times less potent as greenhouse gases as the substances that they are expected to replace.

Table 3.1 Range of lifetimes, ODPs, and GWPs (20-year and 100-yr time horizon) of major ozone depleting substances and HFCs considered in this report (WMO, 2011).

Substance	Lifetime (years)	ODP	GWP(20-yr)	GWP(100-yr)
Chlorofluorocarbons				
CFC-11	45	1	6,730	4,750
CFC-12	100	1	11,000	10,900
CFC-113	85	0.8	6,540	6,130
Hydrochlorofluorocarbons				
HCFC-22	11.9	0.055	5,130	1,790
HCFC-141b	9.2	0.11	2,240	717
HCFC-142b	17.2	0.065	5,390	2,220
Hydrofluorocarbons (saturated)				
HFC-32	5.2		2,470	716
HFC-41	2.8		377	107
HFC-125	28.2		6,290	3,420
HFC-134a	13.4		3,730	1,370
HFC-143a	47.1		5,780	4,180
HFC-152a	1.5		468	133
HFC-161	0.3 ^a		43 ^a	12 ^a
HFC-227ea	38.9		5,480	3,580
HFC-245fa	7.7		3,410	1,050
HFC-365mfc	8.7		2,670	842
HFC-43-10mee	16.1		4,170	1,660
Hydrofluorocarbons (unsaturated)				
HFC-1234yf	10.5 days			4
trans-HFC-1234ze	16.4 days			7

^a From IPCC (2007)

9. A 100-year time horizon is often used when comparing the climate forcing of non-CO₂ greenhouse gas emissions relative to that of CO₂. For emissions of substances with shorter lifetimes compared to the persistence of CO₂ in the atmosphere (~ 100 or more years), the climate forcing significance is highly sensitive to the time-horizon assumed. Therefore, other time horizons may be used depending on the time horizon of the impacts considered. Also, the use of GWPs assumes that the substance is well mixed in the atmosphere. In reality, the global-mean lifetimes and radiative efficiencies of substances with lifetimes less than about half a year are not well mixed and will depend on the location of emission.

3.9 A scenario in which only low-GWP HFCs are used has a low climate influence

As noted in section 3.1, HFC radiative forcing is currently less than 1% of the total radiative forcing. Figure 3.4 shows that if the current mix of HFCs (with an average lifetime of 15 years and an average GWP of 1600) were replaced by low-GWP HFCs (with lifetimes less than 1 month and corresponding 100-year GWPs less than about 20), their contribution to radiative forcing in 2050 would be less than the current forcing, even for the upper range HFC

emissions scenario. Furthermore, it should be noted that if the emissions of such short-lived HFCs were curtailed in the future, their atmospheric abundances and possible adverse climate effects would decrease quickly because of their short lifetimes. On the other hand, this scenario does not take into account the feasibility of using low-GWP HFCs in all applications. In practice, low-GWP HFCs are only one of several alternatives to high-GWP HFCs. These alternatives are discussed in Chapter 4.

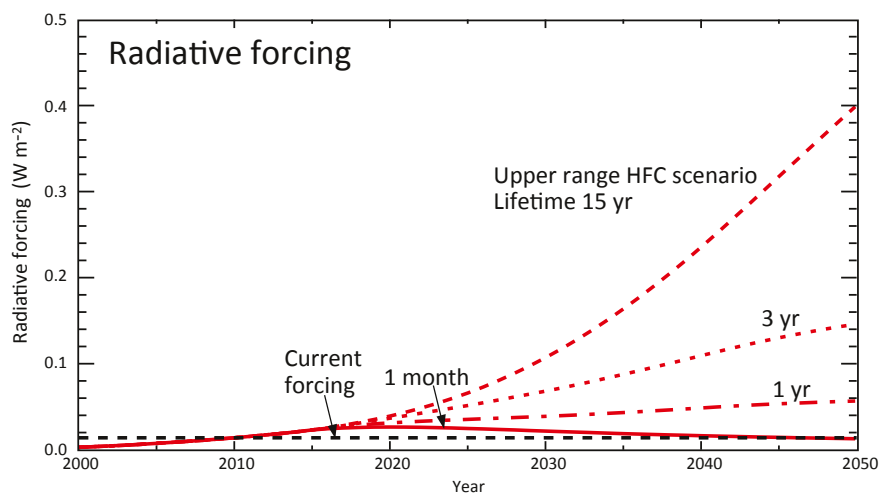


Figure 3.4. Radiative forcing for an upper range HFC scenario and for alternative scenarios with low-GWP substitutes. This figure shows that HFCs with shorter lifetimes than the current HFC mix have a smaller climate influence in terms of lower radiative forcing. All curves are based on the assumptions for growth in demand for the upper range HFC non-intervention scenario of Velders et al. (2009)¹⁰

10. For illustrative purposes, the alternative scenarios assume that from 2015 onwards the same demand for HFCs is met by substitutes with shorter lifetimes and consequently lower GWPs. For the substitutes, a molecular weight of 100 grams per mol is used and a radiative forcing per molecule of $0.2 \text{ W m}^{-2} \text{ ppb}^{-1}$, both typical values for commercially used HCFCs and HFCs. An annual release from the bank of 13% is assumed, typical for refrigeration and air conditioning applications (WMO, 2011).

Chapter 4:

Alternatives to high-GWP HFCs

There is no 'one-size fits all' alternative to high-GWP HFCs.

Low-GWP alternatives are already used commercially in specific applications and in different geographic regions. The current low-GWP systems could be used more widely.

In some sectors, there are no suitable alternatives to high-GWP HFCs at present, but further alternatives are under development.

There are barriers to the adoption of low-GWP systems in a number of sectors. However, the existing uses of alternatives have demonstrated that barriers can be overcome.

4.1 Methods for reducing the influence of high-GWP HFCs on climate have been identified

High-GWP HFCs are used predominantly as ODS replacements for refrigeration and air-conditioning equipment, foam products and other application (Section 1.4). The global demand for such products is increasing with population growth and economic development. Without intervention, the increase in HFC emissions is projected to offset much of the climate benefit achieved by earlier reductions in ODS emissions (Section 3.5).

During the last decade, UNEP technical committees and government bodies have published information about techniques that can be employed to reduce the climate influence of high-GWP HFCs¹¹. They describe best practices for reducing the emissions of HFCs, as well as alternative technologies. Summing up these findings, the alternative technical options for minimizing the influence of HFCs on climate fall into three categories:

Alternatives technologies¹² with zero or low-GWPs that replace the use of high-GWP HFCs include:

- **Alternative methods and processes** (also called 'not-in-kind' alternatives). Commercially used examples include fibre insulation materials, dry-powder asthma medication, and architectural designs that avoid the need for air-conditioners.

- **Non-HFC substances with low or zero GWPs.** Commercially used examples include hydrocarbons (e.g. R-290, R-600a), ammonia (R-717), carbon dioxide (R-744), nitrogen, dimethyl ether, and other substances.
- **Low-GWP HFCs.** Several low-GWP HFCs (with lifetimes of less than a few months¹³) are being developed and introduced. Examples include HFC-1234yf, HFC-1234ze and HFC-1336mzz. These are discussed in Section 3.8.

A number of studies have concluded that combinations of these techniques could achieve substantial reductions in the consumption and emission of high-GWP HFCs.

4.2 Low-GWP alternatives¹⁴ offer the potential to minimize the influence of high-GWP HFCs on climate

As shown in Figure 3.4, alternatives with lifetimes less than several months and low GWPs offer the greatest potential to minimize the influence of HFCs on climate, in terms of direct greenhouse gas emissions. In this report *low-GWP* refers to 100-year GWPs that are below 20.

Tables 4.1 and 4.2 provide examples of alternative substances and methods used at present in specific applications. However, for a number of sectors, further substantive research and development work would be needed to provide effective and affordable alternatives and

11. Examples include EC 2008; EPA 2006; EPA 2010a; FTOC 2011; GTZ 2008; GTZ 2009; IPCC/TEAP 2005; RTOC 2011; TEAP 1999; TEAP 2009; TEAP 2010ab; UBA 2009; UBA 2011ab; UNEP 2010abc.

12. Certain commercial technologies and products are identified for clarity and specificity. However, it is not intended as an endorsement of any specific commercial product.

13. In contrast, the mix of high-GWP HFCs used at present has an average lifetime of 15 years, based on tonnage used. The implications of this are explained in Figure 3.4.

14. The terms "alternatives" and "alternative systems" are used as abbreviations for the three categories of "low-GWP alternatives" listed in Section 4.1.

the relevant infrastructure to support them (see Section 4.8). The most appropriate solutions are expected to differ from sector to sector.

To gain the climate benefits of low-GWP alternative systems, it is important that their total (direct and indirect) lifecycle greenhouse gas emissions are lower than the lifecycle emissions of the HFC systems they replace (Section 3.7). As a result, particular attention needs to be paid to the energy consumption from cradle to grave, including

manufacture, use and disposal. TEAP has reported that systems using low-GWP alternatives are able to achieve equal or superior energy efficiency in a number of sectors, such as domestic refrigeration, commercial refrigeration and some types of air-conditioning systems.¹⁵ In the case of industrial refrigeration, for example, hydrocarbon and ammonia systems are typically 10-30% more energy-efficient than conventional high-GWP HFC systems (TEAP 2010a).

Table 4.1. Alternatives to high-GWP HFCs used in air-conditioning and refrigeration sectors

Sectors where high-GWP HFCs are currently used	Examples of low-GWP alternatives used commercially in specific applications	Examples of alternatives under development
Refrigeration equipment HFC-134a, blends such as 404A, 407A, 407C, 410A, 507A	Ammonia (R-717), ammonia/carbon dioxide, ammonia/water absorption, hydrocarbons (R-290 propane, R-600a isobutane, R-1270 propene), carbon dioxide (R-744), transcritical CO ₂ , water (R-718), adsorption/absorption, solar cooling, cryogenic (open-loop) systems using nitrogen or CO ₂ , eutectic plates based on frozen salt solution	HFC-1234yf, Stirling cycle, cryogenic (open-loop) systems using nitrogen or CO ₂ , air cycle, water vapor compression, magnetism, and improvements in existing methods
Air-conditioning systems for buildings HFC-134a, blends such as 404A, 407C, 410A	Ammonia, ammonia/dimethyl ether, hydrocarbons (R-290 propane, R-1270 propene), carbon dioxide, water, water/lithium bromide absorption, zeolite/water adsorption, desiccant and evaporative cooling, microchannel heat exchangers, architectural designs that avoid the need for air-conditioning systems	HFC-1234yf, HFC-1234ze, HFC-161, new blends, and improvements in existing methods
Air-conditioning systems in vehicles HFC-134a in cars, light trucks. 134a and 407C in buses, trains	Refer to Section 4.6. Commercial introduction is anticipated soon	HFC-1234yf, carbon dioxide, hydrocarbons, HFC-1243zf blends, other proprietary blends

Sources: EPA 2006; EPA 2010a; IPCC/TEAP 2005; RTOC 2011; TEAP 1999; TEAP 2010ab; TEAP 2011ab; UBA 2009, UBA 2011ab, UNEP 2010abd.

Table 4.2. Alternatives to high-GWP HFCs used in foam products, fire protection, aerosols and other sectors

Sectors using high-GWP HFCs	Examples of low-GWP alternatives used commercially in specific applications	Examples of alternatives under development
Foam products HFC-134a, 152a, 227ea, 245fa, 365mfc	Liquid CO ₂ , CO ₂ /water, CO ₂ /ethanol, CO ₂ /hydrocarbons, isobutane, isopentane, cyclopentane, n-pentane, cyclo/iso pentane blends, cyclo/n-pentane blends, n-/iso pentane blends, dimethyl ether, methyl formate, formic acid, chlorinated hydrocarbons e.g. 2-chloropropane, vacuum technology, HFC-1234ze, mechanical processes, fibreglass, rockwool, silicates, cellulose, wool, other fibrous insulation materials, architectural designs that reduce the demand for thermal insulation for heating/cooling	Methylal, inert gases, HFC-1336mzz, HFC-1234ze, FEA-1100, HBA-2, AFA-L1, and improvements in existing methods
Medical aerosols HFC-134a, 227ea	Dry powder inhalers, propellant-free aqueous metered-dose inhaler, soft mist inhalers using liquid jets	CO ₂ propellant, oral or injectable drugs, patches, and improvements in existing methods
Fire protection HFC-23, 122, 227ea, 236fa	Water, water mist, dry chemicals, foams, carbon dioxide, nitrogen, argon, fluoroketone, improved monitoring and alarm systems	2-BTP, and improvements in existing methods
Solvents HFC-43-10mee and c447ef	Aqueous systems, semi-aqueous mixtures, hydrocarbons (e.g. n-paraffin, iso-paraffin), alcohols (e.g. iso-propyl alcohol), solvent-free cleaning methods, procedures that avoid or accommodate oil that was traditionally removed with HFC solvents	Methods that avoid the need for solvent substances

Sources: EPA 2010a; FTCC 2011; HTOC 2011; IPCC/TEAP 2005; MTOC 2011; TEAP 1999; TEAP 2010a; TEAP 2011ab; UBA 2009; UBA 2011ab; UNEP 2010a.

15. Energy efficient sectors include mobile air-conditioning, small air-conditioning units, small and larger reciprocating chillers (<7,000 kW), scroll chillers (10-1,600 kW) and screw chillers (100-7,000 kW).

4.3 Low-GWP alternatives are already in commercial use

Alternatives are being used commercially in a number of specific applications in different regions of the world, as illustrated by Tables 4.1 and 4.2.

Alternatives currently comprise a very small percentage of the market in some sectors, such as refrigerated transport, air-conditioning equipment in large buildings, and spray foam. However, there are other sectors where alternatives already make up a substantial part of the market (Table 4.3). For example, they are used in 36% of new domestic refrigerators and freezers (see Section 4.5). Low-GWP alternatives are used in about 25% of new industrial air-conditioning equipment globally, and in about 65% of new large industrial refrigeration installations (RTOC 2011) such as cold storage, ice skating rinks, and large-scale freezing of food. Further examples are provided in Table 4.3.

In the refrigeration sector, low-GWP alternatives have been used commercially for decades, notably ammonia in industrial cold stores, and hydrocarbons in chemical refineries.

In the foam sector, low-GWP alternatives such as hydrocarbons and CO₂/water are also used commercially, especially in industrialized countries (TEAP 2010a). They comprise 28-76% of the global market for polyurethane foam products (Table 4.3). Fibrous materials (not-in-kind alternatives) comprise 59% of the market for insulation in Western Europe (FTOC 2011).

In the solvents sector, alternatives have already replaced a large percentage of previous ODS uses (TEAP 2010a). Examples include no-clean soldering dominant in electronics manufacturing, and aqueous cleaning which is common in metal cleaning.

The list of new commercial applications using low-GWP alternatives has continued to grow each year. Expert committees have noted the potential to expand the use of existing alternatives, especially those that are already used commercially.

4.4 More alternatives are under development

Refrigeration, air-conditioning and other sectors are constantly evolving in response to a wide range of commercial, environmental, and other pressures. Technological change is a continuing process in industry, with new developments occurring every year. TEAP has noted that climate change issues, as well as developments in refrigerant options, will continue to stimulate equipment innovations in refrigeration and air-conditioning. Companies are in the process of developing new substances and blends (Table 4.1), and associated lubricants and equipment components (RTOC 2011).

Companies are also developing additional uses for existing low-GWP refrigerants. For example, in marine transport refrigeration, the industry is currently developing and piloting low-GWP refrigerants such as CO₂ in marine containers and trailers, and propane in trucks (RTOC 2011). For air-conditioning systems in vehicles, car manufacturers

Table 4.3: Examples of sectors which use a substantial percentage of alternatives

Sector	Examples of alternatives	Use of alternatives in sector		
		Industrialised countries	Developing countries	Global total
Industrial refrigeration systems ^a	ammonia, CO ₂ , hydrocarbons	92 %	40 %	65 %
Industrial air-conditioning systems ^a	ammonia, CO ₂ , hydrocarbons	40 %	15 %	~ 25 %
Domestic refrigerators (compressors) ^b	hydrocarbons	51 %	22 %	36 %
Foam in domestic refrigerators ^c	hydrocarbons	66 %	68 %	67 %
Foam in other appliances ^c	hydrocarbons	38 %	<1 %	28 %
Polyurethane foam boards and panels ^c	hydrocarbons	82 %	21 %	76 %
Fire protection systems ^d	water, foams, dry chemicals, inert gases	-	-	75 %
Asthma medication ^e	dry powder inhalers	-	-	~ 33 %
Solvents ^f	aqueous, no-clean, alcohols, others	> 90 %	> 80 %	> 80 %

Sources: FTOC 2011; RTOC 2011; TEAP 2009ab; TEAP 2010a.

The percentages in this table refer to:

^a refrigerants used in new installations annually; ^b annual production of new equipment; ^c annual consumption of blowing agents; ^d usage or market; ^e annual medical doses; ^f market penetration in solvent applications.

have undertaken intensive research on CO₂ and HFC-1234yf, and the commercial adoption of one or more low-GWP refrigerants is expected soon (Section 4.6).

In the foam sector, companies are developing additional alternatives such as methylal, FEA-1100, and other examples provided in Table 4.2. A number of developing countries intend to adopt low-GWP alternatives for foam products, as part of their HCFC phase-out plans agreed under the Montreal Protocol. For specific types of foam, China and Brazil, for example, intend to use methyl formate and hydrocarbons instead of high-GWP HFCs (MLF 2011ab).

4.5 Case study: Alternatives adopted by manufacturers of household refrigeration and small air-conditioning units

Domestic refrigerators and freezers

About 104 million domestic refrigerators and freezers are produced annually. Each unit can contain 50 - 250 grams of HFC refrigerant, and up to 1kg of HFC blowing agent in the insulating foam. When CFCs were being phased out in the 1990s, hydrocarbon technology was developed for domestic refrigerators to provide a low-GWP alternative to ODSs and HFCs. The use of hydrocarbons has grown to about 36% of the global market for new domestic refrigerators and freezers (Figure 4.1), and is expected to reach about 75% of global production by 2020 (TEAP 2010a). Energy-efficient hydrocarbon systems are now used by refrigerator manufacturing companies in many countries, including: Argentina, China, Denmark, France, Germany, Hungary, India, Indonesia, Italy, Japan, South Korea, Mexico, Russia, Swaziland, Turkey, Brazil and recently in USA (Maté 2010; TEAP 2010a).

Small air-conditioning units

Globally, about 100 million small air-conditioning units are produced annually. Each unit can contain 300 – 3,000 grams of HFC refrigerant. About 70-90 % of global production occurs in China. Recently, the hydrocarbon technology used for fridges has been adapted for small residential air-conditioning units. Production commenced in China in 2011, and the units are mainly exported to Europe at present (JARN 2011). These hydrocarbon air-conditioning units have a high energy-efficiency rating, and employ sophisticated safety measures. This gain is illustrated by the calculation that switching the refrigerant in 180,000 units would prevent 560,000 tonnes CO₂eq of direct emissions during the life-cycle of the units, and avoid indirect emissions of 320,000 tonnes CO₂eq due to improved energy efficiency (GTZ 2010a). Manufacture of similar units is also planned in India and other countries.

4.6 Case study: Technical developments in vehicle air-conditioning systems

Globally, the air-conditioning systems in all new passenger cars have transitioned from CFC-12 to HFC-134a. The refrigerant charge typically varies from 0.4-1.2 kg per vehicle, and in total accounts for about 24% of global GWP-weighted HFC consumption (Figure 1.4) or about 60% of global HFC refrigerant emissions (RTOC 2011; EPA 2010b).

A Life Cycle Climate Performance tool (called GREEN MAC LCCP) has been developed for comparing the direct and indirect carbon emissions of refrigerants for vehicles (EPA 2009). Car manufacturers have evaluated HFC-152a (GWP 133), CO₂ (GWP 1) and HFC-1234yf (GWP 4) as alternative options to replace HFC-134a systems.

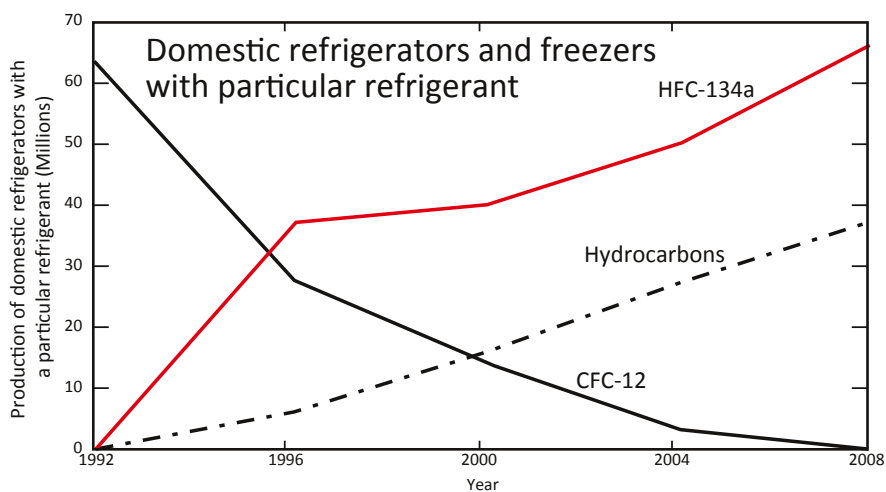


Figure 4.1. Annual global production of domestic refrigerators and freezers, showing changes in the refrigerants used from 1992 to 2008 (RTOC 2011).

Studies have estimated the differences in life-cycle climate performance, although TEAP has reported that all of these options can achieve fuel efficiency comparable to existing HFC-134a systems, with appropriate hardware and control changes (RTOC 2011).

CO₂ systems are being tested in buses and cars (Graz 2009; UBA 2011), and several vehicle manufacturer associations have announced their intention to commercialize HFC-1234yf in new car models. A recent report by RTOC anticipates that companies' decisions on new refrigerants for vehicles are likely to be based on GWPs and energy efficiency, as well as regulatory approval, costs, system reliability, safety and other factors (RTOC 2011). HFC-1234yf and HFC-152a are included in the US EPA's list of acceptable ODS alternatives for new passenger cars, under the Significant New Alternatives Policy (SNAP) program (EPA 2011a), with applications pending for CO₂.

The US EPA plans to initiate the process of removing HFC-134a from the SNAP list for new passenger cars and light-duty vehicles (EPA 2011b), and a national program of CO₂ emission reduction targets for vehicle fleets will allow credits for HFC reductions (EPA 2010b). Commercialization of an alternative is also expected in Europe following an EU Directive that bans the use of vehicle refrigerants that have a GWP above 150 in all 'new-type' cars and light trucks approved after January 2011, and all new vehicles from 2017 (EC 2006).

4.7 Case study: End-user companies pledge to use low-GWP technologies

Supermarkets, food and beverage producers, and diverse other types of companies use equipment and products that contain high-GWP HFCs. Many companies have pledged to reduce or eliminate the use of high-GWP HFCs, and many have already taken significant steps, as illustrated by the following examples:

Supermarkets

About 2000 supermarket premises in Europe have installed low-GWP refrigeration systems, comprising about 2,000 CO₂ systems (transcritical and cascade), ~80 ammonia systems in distribution centers and ~70 hydrocarbon systems (Burhenne 2011; UBA 2009, UBA 2011a). CO₂ systems are used in at least 60 supermarkets in Australia and New Zealand, and CO₂/ammonia systems are being introduced in South Africa (UBA 2011a). A major supermarket chain uses alternative systems in 80 stores in the UK, Czech Republic, Hungary, Poland, Korea, Malaysia, Thailand and the USA, and intends to install alternatives in a total of 150 stores by 2012 (EIA 2011).

Food and beverage companies

Under an international partnership supported by UNEP, five international food and drink companies are committed to replacing high-GWP HFCs with energy-efficient low-GWP refrigerants and insulation in their point-of-sale refrigeration appliances. A food manufacturer has placed more than 800,000 hydrocarbon ice-cream freezer cabinets in Europe, Latin America and Asia. Long-term trials confirmed that they use less energy than high-GWP HFC cabinets (Lingard 2011). Several soft drinks companies have installed more than 420,000 bottle vending machines in China, Europe and Latin America, using CO₂ or hydrocarbons as refrigerant (Azar 2011).

Consumer goods manufacturers and retailers

The Consumer Goods Forum, an international coalition of 650 retailers, manufacturers and other groups in 70 countries, has pledged to begin phasing-out HFC refrigerants in 2015, noting that 'the technologies exist today for our sector to significantly reduce the direct and indirect emissions of the refrigeration equipment we use' (CGF 2010)

4.8 There are barriers to the adoption of low-GWP alternatives but also many ways to overcome them

Technical reports by TEAP and other bodies have identified various barriers to the further adoption of low-GWP alternatives, and also a number of methods to overcome these barriers. UNEP, for example, recently published a report on barriers to the use of low-GWP refrigerants in developing countries and opportunities to overcome the barriers (UNEP 2010c). Some key barriers to further use of low-GWP alternatives are discussed below, together with potential solutions. Alternatives that are used today can provide helpful examples of how barriers can be overcome.

Lack of effective and suitable alternatives in specific sectors

Issue: For a number of applications, low-GWP alternatives are not suitable at present. Examples include the use of spray-foams in situations where it is difficult to apply safety standards; asthma inhalers for specific groups of patients who are unable to use dry-powder inhalers; and air-conditioning and fire protection systems in specific situations. In other cases the technical performance of alternatives may not have been proven.

Potential solutions: As noted in Section 4.4, technology is constantly evolving as a result of research. Technological developments have greatly increased the alternative options available in sectors that use high-GWP HFCs. The

number of low-GWP foam blowing agents, for example, has increased significantly in recent decades. Options now include water, hydrocarbons and CO₂ - and further developments are in the pipeline, such as methylal and HFC-1336mzz (FTOC 2011). Research continues to optimize equipment performance, and further developments in alternative technologies are expected during the next few years (RTOC 2011).

Safety risks due to flammability and toxicity

Issue: Some alternatives (e.g., water, inert gases) are innocuous and generally safe to handle, while others raise safety issues. Safety ratings indicate higher flammability for hydrocarbons, lower flammability for ammonia and HFC-1234yf, and non-flammability for CO₂. Ratings indicate higher toxicity for ammonia, and lower toxicity for hydrocarbons, HFC-1234yf and CO₂. Technicians often lack the relevant know-how and skills for handling alternative substances, and the equipment used currently for high-GWP HFCs may not be appropriate for them.

Potential solutions: Several international organizations have published technical standards that define necessary safety measures, such as EN 378, IEC-60335-2-40, IEC 60335-2-24, IEC 60335-2-89, Draft ISO 5149, and SAE standard J639 for vehicles (MAC). Technical guidelines have also been published (e.g., GTZ 2010b; TÜV-SÜD/ GTZ 2010). The development of additional standards and guidelines would help to address safety barriers in additional sectors.

For the existing commercial use of low-GWP alternatives, safety issues were resolved by R&D and appropriate design changes, such as locating the refrigerant outside a building (e.g., on roofs or in parking lots) so leaks would not endanger the public; limiting refrigerant charge sizes; using automated leak detection and shut-off systems; using containment or hermetically-sealed systems. Investments have also been made in safety equipment and training, so that technicians are able to handle substances safely.

Energy consumption and life-cycle carbon emissions

Issue: At present the thermal performance (energy efficiency) of alternative foam systems is lower than the typical HFC systems in some applications. The energy efficiency of alternative refrigeration (e.g. CO₂) in certain applications is not as high as a conventional HFC system. The energy efficiency of refrigeration equipment varies according to application, design, service practices, ambient temperature and many other factors. Better data are needed to assess and compare life-cycle carbon-equivalent emissions, to ensure that an alternative system will have lower total greenhouse gas emissions than a conventional HFC system.

Potential solutions: As a result of R&D, some existing alternative foam systems are able to achieve energy efficiency (or thermal performance) similar to systems using high-GWP HFCs. Ongoing technological research is expected to bring further improvements in the energy efficiency and thermal performance of foam systems. Tools such as product life-cycle accounting standards (WRI 2011) and Life Cycle Climate Performance models offer the potential to compare direct and indirect carbon emissions. The Multilateral Fund is currently piloting a software tool (MLF Climate Impact Indicator, MCII), which aims to provide simplified calculations of the anticipated carbon emissions of alternative options in HCFC phase-out projects (MLF 2011c).

Other potential environmental impacts

Issue: As shown in Section 3.9, one of the ways to reduce the climate impacts of high-GWP HFCs is to use low-GWP HFCs, which by nature have shorter atmospheric lifetimes. A shorter lifetime leads to a larger fraction of the emissions being degraded closer to the sources and at more rapid rates. Consequently, there are potential adverse environmental effects of such rapid degradation, in particular the production of urban ground-level ozone, and the formation of persistent chemicals such as trifluoroacetic acid (TFA). Some other low-GWP alternatives can also have potential environmental impacts, such as emissions that contribute to photochemical smog.

Potential solutions and outlook: Unless HFC emissions become very large (thousands of times larger than currently seen) in future urban areas, urban ozone production is not expected to be a significant issue. Ozone production has been investigated and the conclusion was that if all HFC-134a is replaced by HFC-1234yf in mobile air conditioning in the USA, emissions of HFC-1234yf would be sufficiently small not to effectively compete with the other sources of urban and natural hydrocarbons that fuel urban ozone production (Papadimitriou et al. 2008; Luecken et al. 2010; Papasavva, et al. 2009). Therefore, it is not expected that HFCs would pose a threat to the violation of air quality regulations.

The potential for the production of trifluoroacetic (TFA) acid from HFC-134a and two potential shorter-lived HFCs (2,3,3,3-tetrafluoropropene, and 1,2,3,3-pentafluoropropene) have been investigated (Papadimitriou et al., 2008, Luecken et al. 2010). These studies estimate that global replacement of HFC-134a with HFC-1234yf at today's levels of use is not expected to contribute significantly to the degradation product TFA (WMO 2011). Of course, if the emissions from regions themselves get hundreds of times larger, these findings will have to be reassessed. Suitable modifications to the structure of the chemicals can also potentially avoid TFA production.

Other barriers

Issue: Other significant barriers include: insufficient technical know-how in companies, a lack of practical skills among technicians, insufficient supply of components and materials or lack of availability in specific localities, inadequate access to proprietary technologies, the cost of generating data for regulatory approval procedures, and higher investment costs.

Potential solutions: Current experience in using alternatives shows that barriers can be overcome in many different ways. For example, by information dissemination, through training courses for technicians and technical staff, with activities to encourage local suppliers, and by building the infrastructure to support the supply of alternative components and materials. Companies that have already adopted alternatives overcame the investment barriers by diverse means, including conventional bank loans, climate protection incentives and, in the case of companies in developing economies, financial assistance provided by ODS phase-out projects of the Multilateral Fund, Global Environment Facility (GEF) projects, climate-related funds, bilateral assistance and other sources.

4.9 There is no 'one-size-fits-all' alternative to high-GWP HFCs

High-GWP HFC substances are primarily used and handled by companies who make or service equipment and products. Decisions about the use of high-GWP HFCs or alternatives are thus made primarily by these companies, and are subject to common commercial considerations, such as:

- Commercial availability of effective and suitable substances or techniques
- Modifications that would be needed in current manufacturing equipment and practices
- Capital and operating costs of using HFCs compared to other options
- Views of customers and the public; and the choices of commercial competitors
- Current and anticipated future requirements of government regulations and industry standards relating to health, worker safety and the environment.

UNEP and other organizations have published several guidance documents to assist in the selection of climate-friendly alternatives, particularly in the context of ODS phase-out (UNEP 2010ab). The appropriate solution for each situation will depend on the application, availability of suitable technology or components, investment and operating costs, feasibility of implementation, and other factors. Thus, there is no 'one-size fits all' solution.

A substantial amount of information about alternative technical options has been evaluated in existing reports. Documents and proposals recently submitted to the Multilateral Fund in the context of HCFC phase-out may also yield valuable new information. A synthesis and update of the existing information is desirable, so that the knowledge gaps can be identified and further investigation and evaluation can be targeted to the areas where it is needed most.

While various alternative options are being evaluated or further developed, there are also some known measures that can be implemented to reduce emissions of HFCs;

- Modifications to the design of products and equipment to reduce leakage (emissions) and the quantity of HFC used in each unit, e.g., a reduced refrigerant 'charge' or component portion in foam.
- Improvements in technical procedures and management practices to reduce HFC emissions during the manufacture, use, servicing and disposal of products and equipment, including the capture and/or destruction of HFCs at end-of-life.

4.10 Going forward

Although, replacing ozone depleting substances with HFCs helps to protect the ozone layer, the increasing use of high-GWP HFCs is likely to undermine the very significant climate benefits achieved by the ODS phase-out to date.

It is still possible to maintain these climate benefits because ozone-friendly and climate-friendly alternatives exist for high-GWP HFCs in a number of sectors. But further work needs to be done before full advantage of these alternatives can be taken. Some remaining tasks include the following:

- Updating the estimates of the climate influence of future HFC scenarios. Relatively few scenarios are available, and a wider range of assumptions about future trends in HFC consumption, emissions, and climate impact need to be explored.
- Further analysis of technical and regulatory barriers to the adoption of low-GWP alternatives, and identification of ways to overcome them. In connection with this, existing experiences on overcoming barriers could be assembled and analyzed.
- Examination of the life-cycle impacts of alternative options to ensure that they provide climate benefits and do not have unacceptable side effects on society or the environment.

By pursuing this and other work, sustainable options for protecting both the ozone layer and the global climate are likely to be found.

References

- Azar, A. (2011) Sustainable refrigeration. Atmosphere2011 Conference, 11-12 October 2011. Shecco, Brussels.
- Burhenne, N. (2011) Natural refrigerants in the European HVAC&R industry: market and policy climate. Atmosphere2011 Conference, 11-12 October 2011. Shecco, Brussels.
- CGF (2010) Consumer Goods Industry announces Initiatives on Climate Protection. Press Release, November 9 2010. Consumer Goods Forum, Paris. Available at: http://www.theconsumergoodsforum.com/pfiles/press_release/Press_Release_2010/2010-11-29-ClimateProtection.pdf
- EC (2006) Directive 2006/40/EC relating to emissions from air-conditioning systems in motor vehicles, Official Journal of the European Union, L 161, 14.6.2006, 12-18
- EC (2008) International Technical Meeting on HCFC Phase-Out, 5-6 April 2008, Montreal, European Commission. Available at: http://ec.europa.eu/environment/ozone/workshop_montreal.htm
- EIA (2011) Chilling Facts III: Supermarkets reducing the climate change impact of refrigeration. Environmental Investigation Agency, London. Available at: www.chillingfacts.org.uk
- EPA (2006) Global mitigation of non-CO₂ greenhouse gases. EPA 430-R-06-005. Environmental Protection Agency, Washington DC.
- EPA (2009) Comparing the impacts of mobile air conditioners. Environmental Protection Agency, Washington DC. Available at: <http://www.epa.gov/cppd/mac/compare.htm>
- EPA (2010a) Transitioning to low-GWP alternatives in domestic refrigeration; and other sectors. Environmental Protection Agency, Washington DC. Available at: <http://www.epa.gov/ozone/intpol/mpagreement.html>
- EPA (2010b) EPA and NHTSA finalize historic national program to reduce greenhouse gases and improve fuel economy for cars and trucks. EPA-420-F-10-014. Office of Transportation and Air Quality, Environmental Protection Agency, Washington DC. Available at: <http://www.epa.gov/oms/climate/regulations/420f10014.pdf>
- EPA (2011a) Lists of acceptable ODS substitutes under the Significant new Alternatives Policy (SNAP) Program. Available at: www.epa.gov/ozone/snap
- EPA (2011b) 40 CFR Part 82. Protection of Stratospheric Ozone: New Substitute in the Motor Vehicle Air Conditioning Sector under the Significant New Alternatives Policy (SNAP) Program; Final Rule. Federal Register 76, 60, 29 March 2011, p.17488.
- FTOC (2011) Report of the Rigid and Flexible Foams Technical Options Committee: 2010 Assessment. UNEP, Nairobi. Available at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports
- Graz, M. (2009) Investigation on additional fuel consumption for R-134a and R-744 AC system in a VW Touran. Obrist Engineering. VDA Winter meeting, Saalfelden, February 2009.
- Gschrey, B., Schwarz, W., Elsner, C., Engelhardt, R., (2011) High increase of global F-gas emissions until 2050. Greenhouse Gas Measurement & Management 1, 85–92.
- GTZ (2008) Natural Refrigerants. Sustainable Ozone- and Climate-Friendly Alternatives to HCFCs. GTZ Proklima on behalf of Federal Ministry for Economic Cooperation and Development, Eschborn.
- GTZ (2009) Natural foam blowing agents. Sustainable Ozone- and Climate-Friendly Alternatives to HCFCs. GTZ Proklima on behalf of Federal Ministry for Economic Cooperation and Development, Eschborn.
- GTZ (2010a) Production of hydrocarbon room air-conditioning systems in China. GTZ Proklima, Eschborn.
- GTZ (2010b) Good practices in refrigeration. A practical manual for technicians. GTZ Proklima on behalf of Federal Ministry for Economic Cooperation and Development, Eschborn.
- HTOC (2011) Report of the Halon Technical Options Committee: 2010 Assessment. UNEP, Nairobi. Available at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports
- IPCC (2000) Special report on emissions scenarios, 750 pp., Cambridge Univ Press, Cambridge, UK and New York.
- IPCC (2001) Climate Change 2001: The scientific basis, 994 pp., Cambridge Univ Press, Cambridge, UK and New York.
- IPCC (2007) Climate Change 2007: The physical science basis, 996 pp., Cambridge Univ Press, Cambridge, UK and New York.
- IPCC/TEAP (2005) Special report: Safeguarding the ozone layer and the global climate system: Issues related to hydrofluorocarbons and perfluorocarbons, 478 pp., Cambridge Univ Press, New York.
- JARN (2011) Green R290 ACs go into mass production. Japan Air Conditioning and Refrigeration News, September 2011.
- Lingard, T. (2011) Unilever Sustainable Living Plan & Natural Refrigerants. Atmosphere2011 conference, 11-12 October 2011, Shecco, Brussels Available at: http://www.atmo.org/presentations/files/100_Unilever-Sustainable-Living-Plan-and-Natural-Refrigerants.pdf
- Luecken, D.J., Waterland, R.L., Papisavva, S., Taddonio, K. N., Hutzell, W.T., Rugh, J.P., Andersen, S.O. (2010) Ozone and TFA impacts in North America from degradation of 2,3,3,3-Tetrafluoropropene (HFO-1234yf), A potential greenhouse gas replacement. Env. Sci. Technol. 44, 343-348.
- Maté, J. (2010) Cool technologies: Working without HFCs. Examples of HFC-free cooling technologies in various industrial sectors. Greenpeace International.
- Miller, B.R., Kuijpers, L.J.M. (2011) Projecting future HFC-23 emissions. Atmos. Chem. Phys. Discuss. 11, 23081-23102.
- Miller, B.R., Rigby, M., Kuijpers, L.J.M., Krummel, P.B., Steele, L.P., Leist, M., Fraser, P.J., McCulloch, A., Harth, C., Salameh, P., Mühle, J., Weiss, R.F., Prinn, R.G., Wang, R.H.J., O'Doherty, S., Grealley, B.R., Simmonds, P.G., (2010) HFC-23 (CHF₃) emission trend response to HCFC-22 (CHClF₂) production and recent HFC-23 emission abatement measures. Atmos. Chem. Phys. 10, 7875-7890.
- MLF (2011a) UNEP/OzL.Pro/ExCom/64/29, June 2011. Multilateral Fund, Montreal. Available at: <http://www.multilateralfund.org/MeetingsandDocuments/currentmeeting/64/English/1/6429.pdf>

- MLF (2011b) UNEP/OzL.Pro/ExCom/64/25, June 2011. Multilateral Fund, Montreal. Available at: <http://www.multilateralfund.org/MeetingsandDocuments/currentmeeting/64/English/1/6425.pdf>
- MLF (2011c) Report on the Multilateral Fund Climate Impact Indicator. UNEP/OzL.Pro/ExCom/64/50, Annex II. Multilateral Fund, Montreal.
- Montzka, S.A., Kuijpers, L., Battle, M.O., Aydin, M., Verhulst, K.R., Saltzman, E.S., Fahey, D.W. (2010). Recent increase in global HFC-23 emissions. *Geophys. Res. Lett.* 37.
- MTOC (2011) Report of the Medical Technical Options Committee: 2010 Assessment. UNEP, Nairobi. Available at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports
- Papadimitriou, V.C., Talukdar, R.K., Portmann, R.W., Ravishankara, A.R., Burkholder, J.B. (2008) CF₃CF=CH₂ and (Z)-CF₃CF=CHF: temperature dependent OH rate coefficients and global warming potentials. *Phys. Chem. Chem. Phys.* 10, 808-820.
- Papasavva, S., Luecken, D.J., Waterland, R.L., Taddonio, K.N., Andersen, S.O. (2009) Estimated 2017 refrigerant emissions of 2,3,3,3-tetrafluoropropane (HFC-1234yf) in the United States resulting from automobile air conditioning. *Environ. Sci. Technol.* 43, 9252-9259.
- Ramanathan, V. (1975) 'Greenhouse effect due to chlorofluorocarbons: Climate implications, *Science*'. 190, 50-51.
- RTOC (2011) Report of the Refrigeration, Air Conditioning and Heat Pump Technical Options Committee: 2010 Assessment. UNEP, Nairobi. Available at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports
- TEAP (1999) HFC and PFC Task Force report. The implications to the Montreal Protocol of the inclusion of HFCs and PFCs in the Kyoto Protocol. October 1999. UNEP, Nairobi. Available at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports
- TEAP (2005) Supplement to the IPCC/TEAP report. November 2005. UNEP, Nairobi. Available at http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports
- TEAP (2009a) Task Force Decision XX/8 Report. Assessment of alternatives to HCFCs and HFCs and update of the TEAP 2005 supplement report data. May 2009. UNEP, Nairobi. Available at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports
- TEAP (2009b) Progress Report of the Technology and Economic Assessment Panel. May 2009, vol. 1, chapter 11, Response to Decision XIX/8. UNEP, Nairobi. Available at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports
- TEAP (2010a) Progress Report of the Technology and Economic Assessment Panel. Assessment of HCFCs and environmentally sound alternatives. Task Force on Decision XXI/9. May 2010, vol. 1. UNEP, Nairobi. Available at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports
- TEAP (2010b) Progress Report of the Technology and Economic Assessment Panel. May 2010, vol. 2. UNEP, Nairobi. Available at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports
- TEAP (2011a) 2010 Assessment Report of the Technology and Economic Assessment Panel. UNEP, Nairobi. Available at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports
- TEAP (2011b) Progress Report of the Technology and Economic Assessment Panel. May 2011, vol. 1. UNEP, Nairobi. Available at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports
- TÜV-SÜD and GTZ (2010) Guidelines for the safe use of hydrocarbon refrigerants. A handbook for engineers, technicians, trainers and policy-makers. GTZ Proklima, Eschborn.
- UBA (2009) Projections of global emissions of fluorinated greenhouse gases in 2050. Climate Change 17/2009. Dessau-Roßlau Umweltbundesamt, Dessau-Roßlau. Available at: <http://www.umweltdaten.de/publikationen/fpdf-l/3866.pdf>
- UBA (2011a) Environmentally sound alternatives in fixed fire protection systems, commercial refrigeration, mobile air-conditioning. UmweltBundesamt (UBA) Federal Environment Agency, Dessau-Roßlau, Germany
- UBA (2011b) Avoiding Fluorinated Greenhouse Gases: Prospects for Phasing Out. Climate Change 08/2011. Federal Environment Agency / Umweltbundesamt (UBA) Federal Environment Agency, Dessau-Roßlau, Germany. 256pp. Available at: <http://www.uba.de/uba-info-medien-e/3977.html>
- UNEP (2010a) Guidance on the process for selecting alternatives to HCFCs in foams. Sourcebook on technology options for safeguarding the ozone layer and the global climate system. UNEP OzonAction Programme, Paris.
- UNEP (2010b) Alternatives to HCFCs in the refrigeration and air conditioning sector. Practical guidelines and case studies for equipment retrofit and replacement. Swedish Environmental Protection Agency and UNEP OzonAction Programme, Paris.
- UNEP (2010c) Barriers to the use of low-GWP refrigerants in developing countries and opportunities to overcome these. UNEP OzonAction Programme, Paris.
- UNEP (2010d) Out of the maze: Montreal Protocol, climate benefits and the green economy. OzonAction Special Issue. UNEP OzonAction Programme, Paris. 24pp.
- UNEP (2011) Synthesis Report: Major findings of the 2010 assessments of the Scientific Assessment Panel (SAP), Environmental Effects Assessment Panel (EEAP), and Technology and Economic Assessment Panel (TEAP). UNEP/OzL.Pro. WG.1/31/3, UNEP, Nairobi. Available at: http://ozone.unep.org/Meeting_Documents/oewg/31oewg/OEWG-31-3E.pdf
- Velders, G.J.M., Andersen, S.O., Daniel, J.S., Fahey, D.W., McFarland, M. (2007) The importance of the Montreal Protocol in protecting climate'. *Proc. Nat. Acad. Sci.* 104, 4814-4819.
- Velders, G.J.M., Fahey, D.W., Daniel, J.S., McFarland, M., Andersen, S.O. (2009) The large contribution of projected HFC emissions to future climate forcing. *Proc. Nat. Acad. Sci.* 106, 10949-10954.
- WMO (2011) Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project. Report No. 52, World Meteorological Organization, Geneva, Switzerland.
- WRI (2011) Product life cycle accounting and reporting standard. World Resources Institute & World Business Council for Sustainable Development, USA.

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