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Abatement of Emissions of Other Greenhouse Gases: "Engineered Chemicals"

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Executive Summary

By means of this study the IEA Greenhouse Gas R&D Programme has initiated a first global economic assessment of the current and future impact on climate resulting from emissions of halogenated greenhouse gases. A bottom-up emission model covering 22 technological sectors in four major regions has been developed for this purpose. Emission estimates for 1996 and projection for 2010 and 2020 have been made. The costs for emission reductions for deep cuts into projected emission levels have been calculated.

The substances covered by this study have contributed emissions of 1100±800 MT CO_2 equivalents[1] per year in 1996 (Figure S1). In terms of their relative contribution to emissions of CO_2 equivalents this corresponds to 3±2% of global emissions of all anthropogenic greenhouse gases. The wide range of uncertainty is due to the poorly quantified net global warming potential of the ozone depleting substances which have an indirect cooling effect on climate through the depletion of stratospheric ozone.

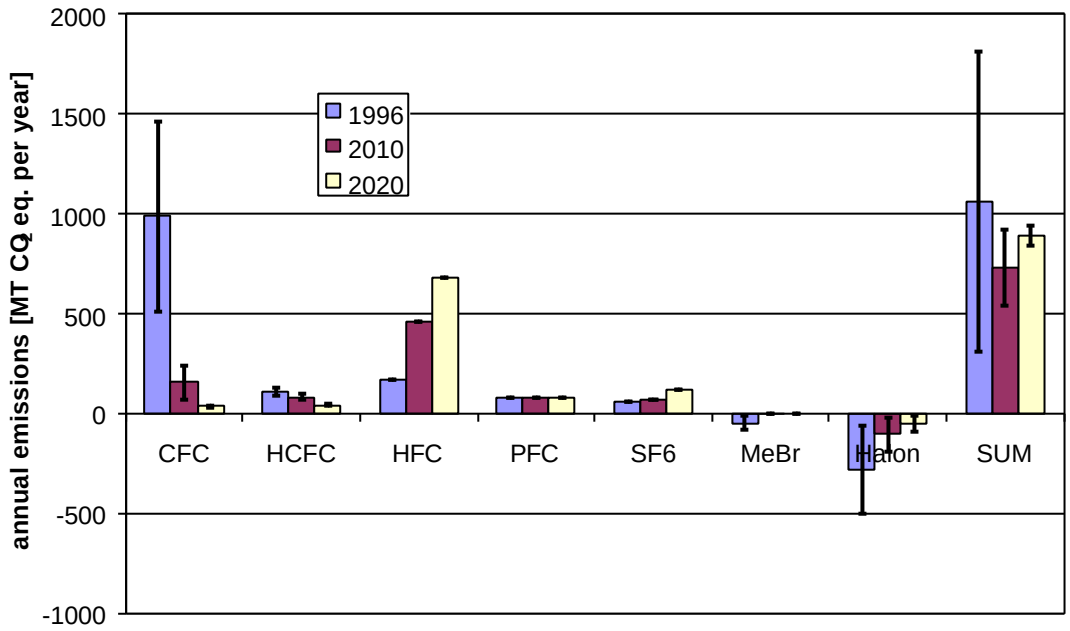

Figure S1 Estimated and projected emissions of different substance classes in 199, 2010 and 2020. Uncertainties due to the indirect cooling effect of ozone-depleting substances are represented through error bars.

For annual emissions of HFCs, PFCs and SF_6 (which are regulated under the Kyoto Protocol and for which global warming potentials are well defined) the relative contribution is projected to increase to 2% (600 MT CO_2 equivalents) of CO_2 equivalent emissions by 2010. This trend is expected to continue, emissions are projected to grow to a contribution of roughly 3% (870 MT CO_2 equivalents) in 2020 compared to 0.9% (300 MT CO_2 equivalents) in 1996.

[1] Emissions of non-CO_2 greenhouse gases are commonly reported as CO_2 equivalents (CO_2 eq.) to permit a convenient comparison to CO_2 emissions. This study uses the new IPCC [2000] global warming potentials (100 year integration period) aggregated for the mix of substances specific for each of the sectors covered by this study (see 1.3.2, 3.1.4 and Annex III Calculations and data tables).

For HFCs, PFCs and SF_6 this study identifies global emission reduction potentials of 260 MT CO_2 equivalents per year in 2010 and 640 MT CO_2 equivalents per year in 2020 at below US$50 (Figure S2). These values correspond to roughly 40% and 75% of projected emissions in 2010 and 2020, respecively. Fairly limited inter-regional differences are anticipated.

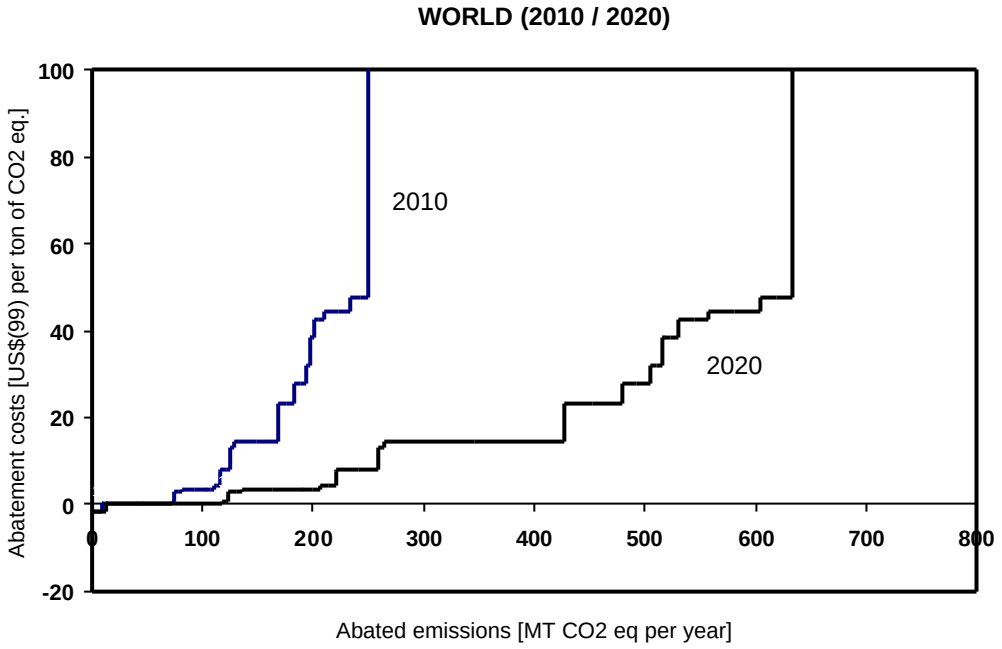

Figure S2 Emission reduction supply curve for HFCs, PFCs and SF_6 in 2010 and 2020.

By 2020 the impact of new emissions of ozone-depleting substances on the climate and the ozone layer is expected to become insignificant if the phase-out schedule of the Montreal Protocol is not delayed. To achieve this goal, emissions of ozone-depleting substances must still be greatly reduced in many developing countries. This transition away from ozone-depleting substances should be continued as part of joint strategy also directed at the climate issue. Appropriate international instruments still need to be created.

CO_2 emissions associated with energy use for refrigeration as well stationary and mobile air conditioning were in the order of 350 MT CO_2 per year in 1996. Aluminium and magnesium production - which lead to emissions of PFCs and SF_6 - are likely to have added another 250 MT CO_2 per year. The specific properties of thermal insulation foams - for which halogenated compounds are often used as blowing agents - have obvious consequences on energy consumption. Associated energy consumption thus also needs to be taken into account in any analysis covering these applications and their alternatives.

Under the 1987 Montreal Protocol, sectors using ozone depleting substances have gone through a rapid policy driven transformation. They have been forced to develop alternative technologies, switch to novel working fluids and to greatly reduce loss rates of relevant compounds into the environment through better leakage control and improved recovery. This process has required significant resources, but has also greatly accelerated the speed of innovation in these sectors. Companies thus today have a large portfolio of technological options to choose from in order to address the next great challenge: climate change.

Abbreviations

AC	air conditioning
AirCo & Heatpumps	stationary air conditioning and reversible heat pumps
CFC	chlorofluorocarbon
ColdStor & FoodProc	cold storage and food processing
CommRef	commercial (supermarket) refrigeration
CWPB	center worked prebake
DomRef	domestic refrigeration
DR	discount rate
EF	emission factor
GWP	global warming potential
GIS	gas insulated switchgear
GIS manuf	manufacture of gas insulated switchgear
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HSS	horizontal stud Søderberg
HC	hydrocarbon
IndustrRef	industrial refrigeration
IEA	International Energy Agency
MAC	mobile air conditioning
MobAirco	mobile air conditioning
MDI	metered dose inhaler
M&D losses	manufacturing and distribution losses
NIK	non-in-kind
OCF	one component foam
ODP	ozone depletion potential
ODS	ozone depleting substance
PFC	perfluorocarbon
PFPB	pointfeeder prebake
PIR	polyisocyanurate
PTFE	polytetrafluoroethene
PU	polyurethane
REF	refrigeration
SAC	stationary air conditioning
SWPB	side worked prebake
TranspRef	transport refrigeration including merchant and naval ships
UNFCCC	United Nations Framework Convention on Climate Change
VSS	vertical stud Søderberg
XPS	extruded polystyrene

Table of Contents

1 Introduction ... 1
1.1 The IEA GHG R&D Programme ... 1
1.2 Structure of this report ... 1
1.3 "Engineered chemicals" in the environment ... 1
1.3.1 Ozone depletion ... 2
1.3.2 Climate impact ... 3
1.3.3 Toxicity, flammability and degradation products ... 5
1.4 Changing use pattern of fluids under the Montreal Protocol ... 6
2 Inventory of available technologies ... 7
2.1 Refrigeration and air conditioning ... 7
2.1.1 Domestic refrigeration ... 9
2.1.2 Small commercial refrigeration ... 10
2.1.3 Supermarket refrigeration systems ... 10
2.1.4 Industrial refrigeration systems ... 10
2.1.5 Refrigerated transport ... 11
2.1.6 Stationary air-conditioning ... 11
2.1.7 Heat pumps ... 12
2.1.8 Mobile air-conditioning ... 13
2.2 Foam production ... 14
2.2.1 PU foams ... 14
2.2.1.1 Rigid PU foam ... 14
2.2.1.2 Flexible PU foam ... 15
2.2.1.3 Integral skin ... 15
2.2.2 XPS foams ... 15
2.2.3 Polyolefin: PE and PP foams ... 16
2.2.4 PIR ... 16
2.2.5 Phenolics ... 16
2.3 Solvents ... 17
2.4 Aerosol application ... 17
2.4.1 Household products ... 17
2.4.2 Medical products ... 17
2.4.3 Technical aerosols ... 17
2.5 Primary aluminium production ... 18
2.6 Semiconductor production ... 18
2.7 Magnesium production and casting ... 19
2.8 Production and use of gas insulated switchgear ... 19
2.9 Other uses for SF_6 ... 20
2.10 By-product emission from HCFC production ... 21
2.11 Manufacturing and distribution losses ... 21
2.12 Industrial products ... 21
2.13 Fire fighting ... 22
2.13.1 Fixed systems ... 23
2.13.2 Portable systems ... 23
2.14 Methyl bromide ... 23
2.14.1 Fumigation in agriculture ... 23
2.14.2 Treatment of wood, structures and durable commodities ... 23
2.14.3 Disinfecting of perishable commodities ... 24
3 Emission scenarios ... 24

3.1 General characteristics of the emission model ... 24
3.1.1 Sectoral structure ... 25
3.1.2 Regions of the model ... 25
3.1.3 Time resolution ... 26
3.1.4 Emitted compounds ... 26
3.1.5 The reference scenario, emission factors and uncertainties ... 26
3.2 Emissions in 1996, 2010 and 2020 in the reference scenario ... 27
3.3 Energy efficiency issues ... 32
4 Assessment of abatement and control options ... 33
4.1 Costing method ... 33
4.2 Consideration of the Montreal Protocol ... 33
4.3 Database ... 34
4.4 Results ... 37
5 References ... 39
Annex I Sectoral modelling of emissions ... 43
Commercial Refrigeration ... 43
Cold storage and food processing ... 43
Industrial refrigeration ... 44
Air conditioning and reversible heat pumps ... 45
Transport refrigeration ... 46
Heat pumps ... 47
Domestic refrigeration ... 48
Mobile air conditioning (MAC) ... 49
Extruded polystyrene (XPS), polyurethane (PU) & polyisocyanurate (PIR) ... 50
Solvents ... 51
Metered dose inhalers (MDI) ... 52
Technical aerosols ... 52
Production of HCFC-22 ... 52
Primary aluminium production ... 53
Semiconductor production ... 53
Magnesium production and casting ... 53
Use of gas insulated switch gear (GIS) ... 54
Manufacture of gas insulated switch gear (GIS) ... 54
Fire fighting ... 55
Fumigation with methyl bromide ... 55
Manufacturing and distribution losses ... 55
Annex II Marginal abatement curves (regions) ... 56
Annex III Calculations and data tables ... 60
Emission data per process and substance class ... 60
Global warming potentials used for different sectors ... 65
Tabulated values of aggregated emissions from different sectors ... 66
Annex IV - Phase-out schedules ... 67
Annex V - Fluid properties ... 73
Annex VI - Overview of options in key sectors ... 77

1 Introduction

1.1 The IEA GHG R&D Programme

The IEA Greenhouse Gas R&D Programme is systematically evaluating the cost and potential for reducing emissions of greenhouse gases arising from anthropogenic activities, especially the use of fossil fuels. The first phase of this Programme concentrated on emissions of carbon dioxide from power generation and particularly on techniques for capture and storage of CO_2. In the second and third phase, attention has also been given to other greenhouse gases, notably methane, and a broader range of sources. The phase 3 plan includes a study of other greenhouse gases. It has been decided that this will be split into two separate studies, one on nitrous oxide (N_2O), and a second study on the "engineered chemicals" such as chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs) and perfluorocarbons (e.g. CF_4). This study deals with the emissions and technical abatement and control options for the engineered chemicals.

1.2 Structure of this report

The structure of this report is set up in the following way: This introductory chapter 1 covers the background of the study and different categories of environmental impacts resulting from emissions of fluorinated compounds. In chapter 2 an inventory of technologies available in the relevant sectors is presented. In chapter 3 emission scenarios until 2020 are derived for four major world regions. The final chapter 4 discusses emission control and abatement options. The report also comprises a number of technical annexes. Annex I covers details on the modelling of emissions for our scenarios. Annexes II and III include regional abatement curves and calculations and data tables, respectively. The annexes IV and V contain the phase-out schedules for ozone depleting substances under the Montreal Protocol and a list fluid properties. The final annex VI gives an overview of the key abatement options and their advantages and disadvantages.

1.3 "Engineered chemicals" in the environment

The term "engineered chemicals" in the context of this study refers to a rather diverse group of volatile halogenated compounds. To study the climate impact of this group of chemicals in a integrated perspective, methyl bromide, carbon tetrachloride and trichloroethane (methyl chloroform) have been added to the set of fluorinated compounds originally to be covered by this study.

For decades synthetic halocarbons have been widely used as refrigerants, blowing agents in foam production, propellants for aerosol applications, solvents, surfactants, fire-fighting and for anaesthetics. Methyl bromide is used as a fumigant of perishable goods and to sterilise soils. Details and additional uses of the halogenated compounds are discussed in subsequent parts of this study.

Many of the engineered chemicals that will be covered by the study have aspects of their use that are closely inter-linked with energy use, e.g. fluids for refrigeration, blowing agents for the production of thermal insulation foams, protection gases in high voltage switch gear applications. An assessment of abatement options of emissions of engineered chemicals has to take into account possible changes of energy related CO_2 emissions that might counteract or amplify the effect of emission reductions.

The atmospheric abundance of the engineered chemicals is typically in the parts-per-trillion (ppt) range. Most of the halogenated engineered chemicals in the atmosphere are almost exclusively of anthropogenic origin. Methyl bromide exhibits several natural and anthropogenic sources of roughly equal relevance [WMO, 1999]. Some natural geologic sources of CFCs, CF_4 and SF_6 are known [Harnisch et al., 2000]. Only CF_4 and methyl bromide exhibited significant natural background concentrations [Harnisch et al., 1996; WMO, 1999].

The major sink of the fully halogenated compounds is photolysis in the middle atmosphere. Most of the partly halogenated chemicals undergo oxidation processes already in the troposphere. This leads to a wide spread of atmospheric lifetime values for this class of compounds from less than one year (methyl bromide) to at least several ten thousand years (CF_4) [WMO, 1999].

The direct radiative effects of emissions of CFCs, HCFCs, HFCs, PFCs and SF_6 have been estimated to be in the order of 25% of all anthropogenic greenhouse gas emissions between 1980-1990 [IPCC, 1990]. However, if indirect cooling effects due to the associated destruction of stratospheric ozone had been included, a significantly smaller contribution would have resulted. Emissions of these ozone-depleting substances have recently significantly declined due to their phase out under the Montreal-Protocol. The non-ozone-depleting HFCs are progressively substituting CFCs and HCFCs in many of their applications leading to rapidly growing emissions rates of HFCs. For this reason (and because of their atmospheric persistence also PFCs and SF_6) they have been included into the Kyoto-Protocol. Reilly et al. [1999] have shown that a failure to control the growth of emissions of these gases can significantly increase the costs of compliance with the Kyoto-Protocol as additional CO_2 reductions have to be achieved in other sectors to compensate for this growth.

1.3.1 Ozone depletion

The class of fluorinated organics has become well known for its contribution to the depletion of stratospheric ozone (mainly through the chlorofluorocarbons). Their stability against common atmospheric oxidation makes it possible that these compounds transport bound chlorine into the stratosphere where it is released through photolytic decomposition. Active chlorine (along with bromine) participate in the now famous catalytic ozone destruction cycle [Rowland and Molina, 1975] that leads to the annual reoccurrence of massive losses of stratospheric ozone above the south and north pole. Different compounds will make differing specific contributions to ozone depletion depending on their stability and number of chlorine (and bromine) atoms contained. Figure 1 visualises the current contributions of various halogenated compounds to the atmospheric halogen burden that leads to ozone depletion. CFCs together are estimated to be responsible for almost 50% of proxy for ozone destruction, with CCl_4 and the halons each adding another10%. Natural emissions of methyl bromide and methyl chloride add another 20% to the organic halogen burden of the atmosphere. The combined contribution of HCFCs, methyl chloroform (CH_3CCl_3) and from anthropogenic emissions of methyl bromide and methyl chloride is estimated to contribute the remaining 10%. It is important to note that uncertainties of the atmospheric budgets especially of the methyl halides remain large [WMO, 1999; Butler, 2000].

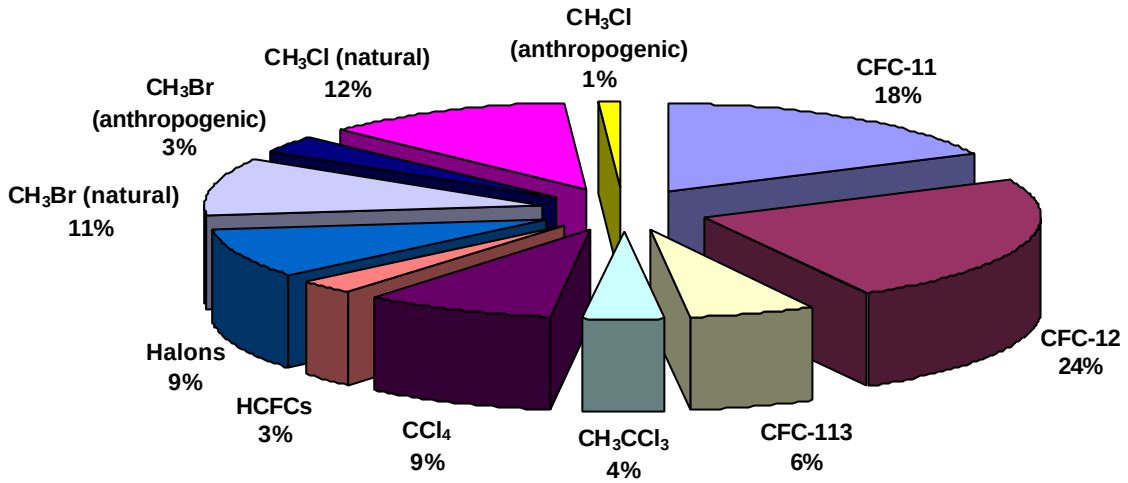

Figure 1 Equivalent chlorine in ozone depleting halogenated gases detected in the 1999 atmosphere [Butler, 2000].

1.3.2 Climate impact

A significant contribution of fluorinated compounds to anthropogenic global warming was first proposed by Wang et al. [1980]. The specific ability of a molecule to contribute to global warming results from its atmospheric lifetime, its spectroscopic properties and the current composition of the background atmosphere. Relative to a mass unit of carbon dioxide this specific ability is quantified as global warming potential (GWP). A certain default integration period has to be assumed for these calculations. Under the regime of the Kyoto protocol a period of 100 years is used. The choice of this value has a strong influence on the relative ranking of compounds, i.e. the longer the integration period the higher the GWP of long-lived compounds like PFCs.

The following expression[2] defines the GWP of a substance relative to CO_2 [IPCC, 1990].

$$GWP_{i,n} = \frac{\int_0^n a_i \cdot c_i(t) \cdot dt}{\int_0^n a_{CO_2} \cdot c_{CO_2}(t) \cdot dt}$$

[2] The term a_i is the instantaneous radiative forcing due to a unit increase in the concentration of trace gas I, c_i is the concentration of the trace gas, i, remaining at time t, after its release and n is the number of years over which the calculation is performed. The corresponding values for carbon dioxide are in the denominator [IPCC, 1990].

Their direct global warming potentials (GWP) ranges from a few hundred to more than 20,000 times CO_2-equivalent when calculated over a 100-year period [IPCC, 1996]. Within the stratosphere, the chlorinated and brominated engineered chemicals are the prime causes of ozone depletion. This contribution to ozone depletion adds an indirect cooling to the radiative effect of these compounds. In the case of the so-called halons (bromofluorocarbons) and methyl bromide this indirect cooling effect by far outweighs the positive direct effect. The uncertainties associated with net global warming impact of these compounds are large [IPCC, 1996, WMO, 1999; Harnisch et al., 1999; IPCC, 2000]. Figure 2 shows the range of GWP values for the ozone depleting substances and the HFCs, PFCs and SF_6 to which the issue of indirect effects does not apply. The corresponding numerical values for an extended set of compounds plus their atmospheric lifetime are presented in Table 1.

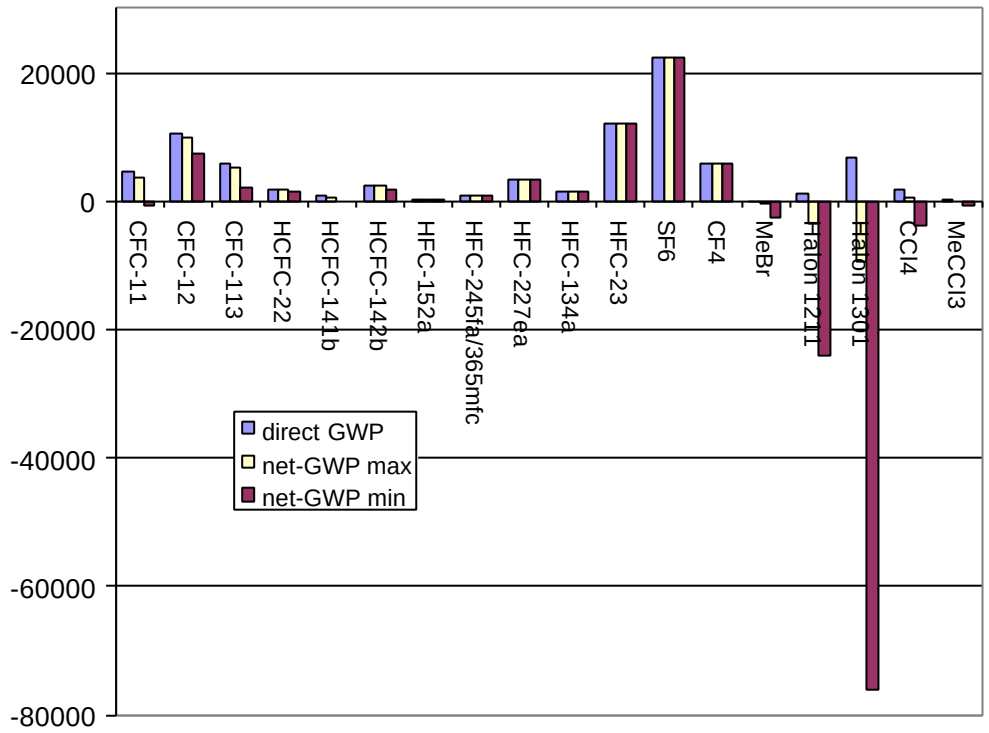

Figure 2 Direct, minimum and maximum GWP (100 years) values for the key compounds covered by this study [IPCC, 2000].

In the Kyoto-Protocol it has been agreed to use GWPs with a 100 year integration period. This 100 year timeframe is believed to appropriately correspond to the typical time scales in which anthropogenic modifications of the world climate system are expected to take place. Integration periods of 20 or 500 years which were also used quite frequently are thought to over-emphasise short term or very long term impacts. In this study the 100 year integration period is thus also exclusively used. However, this study departs from the conventions of the Kyoto Protocol in using updated GWP dates from the forthcoming IPCC Third Assessment Report [IPCC, 2000a]. A number of factors have contributed to fairly significant revisions of values for many of the engineered chemicals. It was deemed inappropriate for a scientific analysis to continue to use the outdated values outside of the contractual framework of the Protocol.

Frequently have assessments of the climate impacts of ozone-depleting substances used the direct GWPs which can be calculated in a straight forward manner involving limited uncertainties. Due to the inadvertent associated destruction of stratospheric ozone (see above) this approach does not yield a sound estimate of these compounds' impact on the climate system. Recognising these shortcomings many authors have recently started to use net-GWPs. Often the maximum net-GWPs were used which take into account only a minimum correction. In this study the average value of the maximum and the minimum net-GWPs is used as default GWP value for the ozone depleting substances.

Table 1 Direct, minimum & maximum net GWP (100 years) and atmospheric lifetime [IPCC (2000)].

	direct	min net	mean net	max net	atm. lifetime [years]
CFC-11	4600	-600	1500	3600	45
CFC-12	10600	7300	8600	9900	100
CFC-113	6000	2200	3700	5200	85
HCFC-22	1900	1600	1750	1900	12
HCFC-141b	700	-5	280	570	9
HCFC-142b	2400	1900	2100	2300	19
HFC-152a	160	160	160	160	1.4
HFC-365mfc	900	900	900	900	10
HFC-134a	1500	1500	1500	1500	14
HFC-23	12000	12000	12000	12000	260
SF_6	22200	22200	22200	22200	3200
CF_4	5700	5700	5700	5700	50000
MeBr	5	-2600	-1550	-500	0.7
Halon 1211	1300	-24000	-13800	-3600	11
Halon 1301	6900	-76000	-42650	-9300	65
CCl_4	1820	-3900	-1620	660	35
$MeCCl_3$	140	-560	-280	0	5

1.3.3 Toxicity, flammability and degradation products

Generally an evaluation of the environmental performance of compound should not be restricted to global phenomena like ozone depletion and climate change, but should also include more local issues like toxicity and flammability. Detailed information is also contained in Annex V - Fluid properties in the back of this study.

Toxicity:

Most of the commercial fluorinated compounds covered by this study are used in technical applications because they are non-toxic even at very high concentrations. Among the exceptions are perfluoro-propylene (very toxic) and HFC-123 (toxic at high concentrations). In addition there is also a number of isomers of certain commercial halogenated compounds that exhibit significant toxicity. Methyl bromide is very toxic at low concentrations.

Flammability:
Most of the fluorinated compounds covered by this study are used in technical applications because of their non-flammability. Notable exceptions that can be ignited under ambient conditions are:

- HFC-152a
- HFC-143a
- CH_3F

Methyl bromide is also flammable.

Degradation products:
Most of the compounds covered by this study undergo the general degradation pathway to carbon dioxide (CO_2), hydrogen chloride (HCl) and hydrogen fluoride (HF). The later two are removed from the atmosphere by precipitation. Resulting concentrations of chloride and fluoride in rain will generally remain orders of magnitude below natural background concentrations and result in no measurable environmental damage on their decomposition pathway. A few compounds will however be degraded into very stable products like trifluoroacetic acid (TFA) which is likely to accumulate in aquatic ecosystems [Tromp et al., 1995]. Levels of TFA recently detected in the environment (Frank et al. [1996]; Wujcik et al. [1999]) exceed the concentrations expected based on known anthropogenic sources [Jordan and Frank, 1999]. Measurements of von Sydow [1998] and Scott et al. [1999] in (aged) ocean waters indicate that TFA may exhibit a significant background concentration in oceans. These findings suggest that natural sources of TFA also exist and possibly even outweigh the anthropogenic source.

1.4 Changing use pattern of fluids under the Montreal Protocol

During the past 13 years significant changes in use pattern of fluorinated fluids have already occurred in response to the 1987 Montreal Protocol and its subsequent amendments [UNEP, 2000]. In industrialised countries many relevant sectors have already completed their transition away from ozone-depleting-substances (ODS). Developing countries have also made considerable progress to reduce their usage ODS in existing applications and to prevent a growth of their use in expanding applications. In the Article 5 of the Montreal Protocol it was agreed to have a two speed approach of phasing-out these compounds depending on the economic resources of countries. The industrialised countries (non-Article 5 countries) which were the main emitters of ODS agreed to take the lead through a rapid phase-out. The developing world (Article 5 countries) were given more time to seek for alternative solutions and convert their processes. A Multilateral Fund (MLF) was created to facilitate a technology transfer to the Article 5 countries through information exchange and investment assistance. Please refer to the Annex IV - Phase-out schedules in the back of this study for a detailed list of phase-out schedules for individual compounds.
Figure 3 shows that until 1988 global usage of fluorinated compounds was growing rapidly. After this date especially CFCs were gradually replaced by alternative substances and technologies or were contained and recovered more effectively in other applications. This led to a significantly reduction in consumption of CFCs which was partly compensated by increases of global consumption of HCFCs and HFCs with reduced or no contribution to ozone depletion.
This study looks at the time interval from 1995 to 2020. This choice of the base year does not capture much of the transition which occurred under the Montreal Protocol since the late 1980´s. Our neglecting of the time prior to 1995 is purely due to the scarcity of reliable data on fluid use and emissions on a sectoral level prior to 1995. This approach should by no

means be misinterpreted as a failure to recognise the achievements recently made by the many sectors formerly using ozone depleting substances.

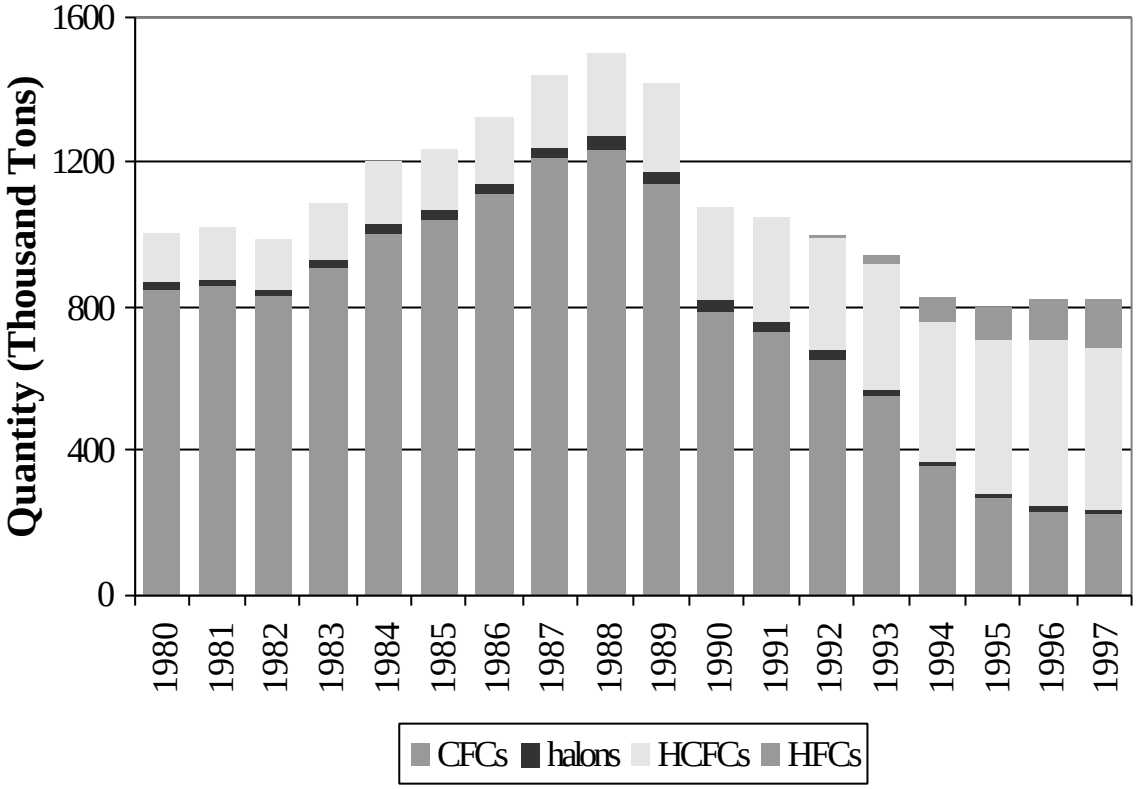

Figure 3 Global usage of CFCs, HCFCs, HFCs and Halons - after McFarland (2000).

2 Inventory of available technologies

This chapter describes different technological options available and under development in the 22 sectors covered by this study. Applications in most of these sectors tend to be fairly diverse with different technologies competing against each other. Though some technologies could achieve dominance in the mass markets and others seem confined to niche applications, a wide range of technological options is available. A changing economic or regulatory framework could rapidly shift market preferences in most sectors covered by this study. Therefore a differentiation between current, alternative and evolving technologies was not attempted.

2.1 Refrigeration and air conditioning

In refrigeration and air-conditioning, the dominant technology is the cold vapour compression cycle. Ideal fluids for this cycle are substances with properties that allow phase change at the desired delivery temperature and at a temperature above ambient at pressures near atmospheric pressure. CFCs used to be the prime choice before the Montreal protocol, since the fluids were inexpensive, non-toxic, non-flammable and had good thermodynamic properties.

Fluid Options

Under the Montreal protocol, the CFCs in most applications were rapidly phased-out and replaced with compounds like HCFCs, HFCs and "natural refigerants" like hydrocarbons (HCs) or ammonia with lower or no ODP (Table 2). Some of the replacement substances have high GWP values e.g. HFC which creates in conjunction with the Kyoto protocol the demand for emission control or alternative fluids and technologies.

Table 2 Fluids used as alternatives to Ozone Depleting Substances [UNEP, 1998a].

ODP Fluid	Alternative fluid
CFC11	HCFC-123, HFC-134a, HFC blends, ammonia
CFC12	HCFC blends, HFC-134a, HFC-152a, ammonia, HC-290, HC-1270
CFC114	HCFC-124, HFC under development, ammonia
CFC blend 502	HCFC blends, HCFC-22, HFC blends, HFC-152a, ammonia, HC
HFC/CFC blend 500	HFC-134a, HFC-152a, ammonia
HCFC22	HFC blends 404a, 407c, ammonia, HC-290, HC-1270

Alternative Technologies

A number of alternative technologies are under evaluation (Table 3). Air is a fluid with zero GWP, but the thermodynamic properties make the air cycle less energy-efficient than other alternatives. Absorption refrigeration is a proven alternative technology which has been used only to a small extent for refrigeration, but mainly for air-conditioning. Stirling cooling engines and thermoelectric refrigeration are presently under development but not available as commercial products in a wide range.

Table 3 Non-in-kind alternative technologies [UNEP, 1998a]

Technology	Advantage	Disadvantage
Stirling/Vuilleumier cycles	efficiency	high cost, short lifetime
Absorption/Sorption	well established	low efficiency
Desiccant cooling cycles		not commercially available, large volume
Transcritical CO_2 cycle	efficiencies equivalent to HCFC-22 cycle	not commercially available

Recovery and Leakage Control

In the short term recovery and leakage control are likely to make the largest contribution to reduce refrigerant emissions. Recovery refers to the proper extraction of refrigerant during servicing and at end of life. For many applications it used to be and sometimes still is common practise to completely vent the refrigerant or collect only a fraction it due to lack of proper equipment, time or awareness. Improved leakage control can also greatly reduce emissions. This can be done through improved training of workers, allocation of sufficient time for the commissioning procedures and changes in design, e.g. improved seal materials or welded pipes instead of fittings.

Reducing Cooling Demand

Options often overseen in the technical literature are those that avoid / reduce the demand for external cooling. On a technical level this could be through evaporative cooling. The effect on cooling demand originating from economic developments in agriculture and transport can also be quite significant.

2.1.1 Domestic refrigeration

Small refrigeration appliances for household application usually utilise the cold vapour compression cycle, which consists of a hermetically sealed circulation loop that contains the fluid and connects evaporator, condenser and compressor. The consumer demand for appliances that need no maintenance over their lifetime has resulted in very low leakage rates. This is achieved by hermetically contained systems that are charged for their lifetime in the production process. Refrigerant loss occurs mainly due to mechanical damage of the evaporator coil or other failures, which also end the lifetime of the appliance. Minor loss also occurs in the manufacturing process while charging the cycle.

Following the phase-out scheme of the Montreal protocol a change of refrigerant has taken place from the most common CFC-12 mainly to HFC-134a, since 134a is close to a drop-in replacement without excessive modifications or system re-engineering. Industries in developing countries continue to charge the larger part of appliances with CFC-12 due to cost reasons.

The change to HFC is rather simple since only minor changes are necessary in the design of refrigeration devices (different size of evaporator, synthetic lubricant in compressor). However, the disadvantage is the GWP of the fluid.

Hydrocarbons have the same good thermodynamic properties as HFC but a significantly lower GWP. The disadvantage is the flammability of the fluid, which makes redesigns in the manufacturing process necessary. Since handling of the fluid mainly takes place on the manufacturing site, the conversion to HC in hermetic systems has proved to be easier than expected, which seems to be the reason that on average, 45% of new household refrigeration equipment uses HC as a fluid in Europe. In Northern Europe, virtually all new appliances are charged with HC [IPCC, 2000b].

Emission reduction in this field can be achieved in the reduction of charge or by refrigerant recovery and recycling/destruction at the end of the lifetime of the appliance. Although the efficiency of ammonia cycles is superior to other GWP and ODP refrigerants, the lack of small components, especially compressors is currently the limiting factor to the application on small scale refrigeration.

CO_2 is seen as a competitive alternative refrigerant despite the high pressures for the supercritical cycle. Presently, systems are still in the R D & D phase.

Other alternatives are NIK technologies e.g. absorption cooling which is frequently applied in camping equipment, hotel refrigerators and locations without grid connection. Although this method is state-of-the-art, the poor efficiencies and the unwanted heat loads make it unsuitable in household application.

Cooling with the thermoelectric effect has a comparably low efficiency in conjunction with high initial costs and further development is not foreseen at present.

Stirling cycles are mainly used for cryogenic cooling due to the high initial cost of these systems.

Refrigeration with thermo-acoustic effects in principle is very simple in construction but is currently used commercially only in cryogenic cooling. For higher temperatures, only lab prototypes exist and the efficiency is seen critical in the high temperature application.

Refrigeration can be realised using the electro-osmosis effect by connecting an electrical current to a membrane. This technology is still in the R&D phase and no statement can be made on the efficiency so far.

Evaporative cooling is a comparably simple technology for cooling at high temperatures e.g. for the cooling of buildings. Systems are available on the market, but the market share is low even in dry and hot climates [van Gerwen and Vervoerd, 2000].

2.1.2 Small commercial refrigeration

Small commercial applications for refrigeration are vending units of chilled beverages, coolers for cellars or flow chillers for beverages in restaurants and bars, small display units in shops, drinking water coolers, cooling units for machinery such as computers or copiers or through-the-wall air-conditioning. The construction is normally aimed to provide a longer service life than in domestic application, which makes maintenance and refrigerant replacement an option for some systems. In 'developed countries', maintenance and repair is usually done by trained specialists.

The small commercial applications normally use the same machinery types as household refrigeration i.e. hermetic cold vapour compression cycles. Therefore, the choice of fluids is similar: Prior to the Montreal protocol, units were charged with CFC-12, which was later replaced mainly with HFC-134a and increasingly hydrocarbons.

2.1.3 Supermarket refrigeration systems

Supermarket freezer and refrigerated displays as well as cold stores are commonly based on the cold vapour compression cycle. The fluid mainly serves as refrigerant and transfer fluid which results in large charges depending on the distance between compressor unit and heat exchangers. Depending on the temperature level the fluid charge is 1-1.5 kg/kW cooling capacity for medium temperature and 3-4 kg/kW cooling capacity for low temperature [UNEP 1998]. Typical refrigerants for medium temperatures prior to the Montreal Protocol were CFC-12, HCFC-22 and blends of CFC-12 with CFC-115. For low temperature application, HCFC-22 or blends of CFC-12 with CFC-115 were used [UNEP, 1998]. Later, a shift to HFC 134a, 404A/507, 407c and 410a replacements was made to comply with the Montreal Protocol.

Annual emission rates are estimated to fall in the range from 15% to 30% [UNEP, 1998] for direct expansion systems. New installations in 1998 can exhibit loss rates around at 3% if carefully designed and maintained [Ecofys, 1999].

Reducing the charge e.g. with more localised systems also reduces the leakage losses: 4% per year [A.D. Little, 1999]. Systems with secondary loops for the warm or the cold side of the refrigeration process also reduce the needed charge and leakage to approx. 2 % p.a. [A.D. Little, 1999].

Alternative fluids are HCs and ammonia. Ammonia has been used in the starting phase of refrigeration up to the 1930s due to its excellent thermodynamic properties, although it is flammable and toxic. HC are also flammable and substitutes HFCs or CFCs in cold vapour compression cycles without a system change. Therefore HC and ammonia are best used in decentralised refrigeration units with secondary carrier loops e.g. with liquid ice or brine.

2.1.4 Industrial refrigeration systems

Industrial refrigeration systems provide process refrigeration, or refrigeration for conservation or for freezing of food, chemical and medical products. Ammonia and the cold vapour compression cycle have dominated this market. Hydrocarbons and ammonia have always had a significant market share of this sector. Ammonia is also 0-15% more efficient than comparable cold vapour compression cycles. Despite the higher cost of HFC, most cold vapour compression cycle systems have been converted with this drop-in alternative. Part of the systems is also charged with HCs since the size of the systems allows separate installation of the refrigeration units in a safe place while a secondary loop carries the heat load. HCs are also used in sectors where the handling of flammable chemicals is common. Another potential technology alternative is the use of water as a fluid.

For the very low temperature range between –60° to –90°C, substances have been found that can replace the halon-1301 in most applications. Blends of HFCs and HFC/PFC/HC can be used in most cases, for the low temperature range cascade systems with cold vapour compression cycles and CO_2 cycles are economically favourable [UNEP, 1998].
The air cycle is also occasionally used for food freezing and liquefied gas production [van Gerwen and Vervoerd, 2000].

2.1.5 Refrigerated transport

Transport refrigeration covers reefer ships, containers, railcars and road transport. The insulation material will be covered mainly in the foam section while refrigeration systems will be dealt with in this section.
Movement, handling and engine vibrations create plenty of mechanical stress for cooling systems so that sophisticated engineering is required. However, leakage rates are considerably higher than in stationary applications. Systems as well as refrigerants have to meet the demands of several standards and requirements, and the design has to consider the operation in several different climates and conditions. Replacement of HFC-134a, the substitute for ODP CFC-12 and azeotrope CFC-502, is therefore difficult to find: The fluid should in no way harm the environment i.e. be non-toxic and non-flammable if it escapes and the system should be suited for all sorts of operation conditions.

Road/railway

Leakage rates are estimated to be around 5% for rail transport and 15 % for road transport [Öko-Recherche, 1998]. Some sources indicate leakage rates of 40% in older installations and 7% in present new installations [Ecofys, 1999; and references therein].
In this segment HFC blends (mainly 404A) and HFC-134a have replaced CFC-12 and CFC-502. 25% of new installations are assumed to be charged with HCFC-22 [IPCC, 2000b]. Potential fluid alternatives with lower GWP would be HCs, ammonia and CO_2. However, international safety legislation prohibits the use of flammable or toxic fluids in many applications, which excludes HCs and ammonia.

Ships/containers

Refrigerated ship transport and reefers use fairly large amounts (several tons, Öko-Recherche [1996] assumes 4000 kg per ship) of charge due to the great cooling demand, but also due to the large dimensions of the ship. The extended piping system is vulnerable to damage from handling of goods with heavy machinery and from mechanical stress e.g. vibrations, torsion and difficult to check for leaks. The mean annual leakage rate is estimated to be around 10% [Öko-Recherche, 1996]. The individual charge of container refrigeration units (typically 7kg, [Öko-Recherche, 1996]) multiplies with the large numbers (world wide >500,000) to considerable amounts.
HFC-134a and, in the future, the blend HFC-410a are expected to be the most commonly used CFC substitute in this application [Harnisch & Hendriks, 2000; UNEP, 1999a].

2.1.6 Stationary air-conditioning

Building air conditioning (AC) systems are distinguished in small, typically room AC systems, indirect cooling or secondary chiller systems and centralised direct exchange (DX) systems.
The need for air conditioning can be reduced by improved energy efficiency (smaller heat loads) in the building, by controlling irradiation and improved insulation and by utilising

passive cooling (e.g. drawing intake air from underground pipe systems or cold air circulation at night). Fluid alternatives are treated in each section.

Room AC systems

The range of 2-10 kW cooling capacity is covered by compact systems such as room air conditioners, packaged terminal air conditioners, duct-free air conditioners and split systems. These systems are applied in residential houses and apartments, small shops and offices and usually have a charge of typically 0.3 to 0.4 kg of refrigerant per kW cooling capacity. Prior to the Montreal protocol, HCFC22 has been applied in almost all systems and HFC (R410a and R407c) blends are seen as the main alternative for the smaller systems [UNEP, 1998a].

Secondary chillers

Secondary chillers transport cool fluid as energy carrier from the refrigeration unit to the individual rooms. The refrigeration is mostly located in the basement or on the roof of the respective building. The most common secondary loop fluid is water, the primary refrigerant used to be CFC-11 or CFC-12 as well as HCFC-22 prior to the Montreal protocol. The primary fluids have been substituted with zero-ODP HFC-134a and HFC blends, although HFC-134a cannot be used as a drop-in replacement [March, 1998; UNEP,1998]. Main HFC blends used are R410a and R407c [UNEP, 1999a]

Since the primary refrigeration unit is remote from the user, the fluid can be chosen more freely. Applied feasible options are ammonia, CO_2 and HCs. Intensive research for trans-critical CO_2-cycles are expected to reach commercialisation within the next 5-10 years [UNEP, 1999a]

Centralised systems

Centralised systems provide conditioned air: Intake air is filtered, cooled or heated, moisture is removed before the air is distributed throughout the building. Since large space for handling large amounts of air is required, the AC units are often placed on rooftops or in basements, again far from the users. The traditional refrigerant for direct heat exchange (DX) systems used to be HCFC-22, which is now commonly replaced with HFC blends, namely R407c and R410a.

Toxicity and flammability are a concern since refrigerant and air may come in direct contact with the air supply in case of leaks in the piping, which would distribute traces of refrigerant in the whole building. Therefore, secondary loops between the refrigeration unit and the heat exchangers need to be installed if alternative refrigerants are used.

2.1.7 Heat pumps

Heat pumps use the cold vapour compression cycle to absorb heat at a low temperature level and transfer it to a higher temperature level. Heat pumps are used to provide heating and/or cooling to buildings and to recover waste process heat.

In the built environment, the heat pump can be used in two ways: Either the heat pump absorbs heat from the ambient and delivers high temperature heat for use in buildings or it absorbs heat from the building and delivers this heat to the ambient to provide cooling. Some heat pumps are designed only to deliver heat into the building, in Northern America the share of ‘reversible’ heat pumps that provide heating and cooling is comparably high.

Almost all heat pumps for the built environment operate with the cold vapour compression cycle with typically 0.3 kg/kW HCFC-22 as working fluid [UNEP, 1998a]. HFC-134a has not found acceptance in this application, but the HFC blends 410a and 407c are used in commercialised products in Europe, US and Japan. CO_2 is under research as alternative fluid.

Smaller units for residential use with HC fluid are available from manufacturers in Northern Europe [UNEP, 1998a].
For industrial application in waste heat recovery, several fluids are used depending on the process temperature. In some cases, the process product can be used as the fluid (mechanical vapour recompression). This method is used to recover the vapour heat for the distillation process. Other applications include the use of electric heat pumps with a wide variety of fluids (including ammonia, HC), absorption heat pumps often use water and lithium bromide as the working pair [UNEP, 1998a].

2.1.8 Mobile air-conditioning

Cars / truck

A/C systems in cars and trucks can be distinguished by the charge amount, while the other characteristics remain similar. While charges for cars range from 0.5 kg for small cars to 1.0 kg for large vans, the charges for trucks are 1.0 kg for trucks of less than 16t max weight and 1.2 kg for trucks with more than 16t max weight [Öko-Recherche, 1999]. UNEP [1998a] assumes an average of 1.18 kg per vehicle in all mobile AC applications. [Öko-Recherche, 1999] indicates that average charges in new German cars have been reduced from 0.88 to 0.77 kg and in foreign cars from 0.86 kg in 1995 to 0.75 kg respectively in 1997.
While cars and trucks mainly used CFC-12 as a fluid for air-conditioning systems before the Montreal protocol, almost all manufacturers have now switched to HFC-134a. High losses in leaks and maintenance have been reduced by design improvement and staff training from 30% [UNEP, 1998; Öko-Recherche, 1999] to 10% in new systems [Öko-Recherche, 1999]. However, leakage rates of household refrigeration units or equivalent hermetic systems cannot be achieved as long as the mechanical energy of the vehicle engine has to be transmitted to the compressor with a drive shaft.
An alternative fluid for this application, where extreme conditions and close proximity between user and refrigeration system prevail is CO_2. The European Union RACE Project (Refrigeration and Automotive Climate Systems under Environmental Aspects) has examined the applicability of the transcritical CO_2 cycle and concludes that it appears to be a promising technology [RACE, 1998]. Several car manufacturers have started development of this technology and expect commercialisation between 2005 and 2008.
In Europe there is a trend towards a higher market penetration of car AC systems, while in the USA and in Japan car AC market penetration stagnates at an already high level [Öko-Recherche, 1999]. Due to availability of low-cost CFC-12 in Africa and South America, it has been observed that the initial charge with HFC-134a is replaced or topped up with CFC-12 during maintenance and repair in many cases [UNEP, 1998a].

Busses

The heat load of passengers and irradiation in buses needs to be removed in order to maintain comfortable conditions. Therefore, cold vapour compression AC systems are rather widespread in developed countries. [Öko-Recherche, 1999] assumes a refrigerant charge of 10 kg in new systems. HCFC-22 is successively replaced by HFCs, mostly HFC-134a in new systems, both with relatively high leakage rates. Retrofits with HCFC, HFC and HC are available for systems in use. Ammonia, HC, CO_2 and air cycle alternatives are under examination [UNEP 1998a].

Railroad

In passenger railcars as well as in buses, CFC-12 and HCFC-22 used to be the main fluid, which is replaced by HCFC blends and HFC134a in new systems. [Öko-Recherche, 1996] assumes a charge of 17 kg per railcar. In some cases, due its robustness occasionally the Joule-Brayton (air-) cycle is used for air conditioning in trains (e.g the first generation German high speed trains) despite its poor energy efficiency.

Aircraft

Aircraft AC is in most cases based on the air cycle, i.e. that air is used as the fluid in an open refrigeration cycle. The supply air is often taken from the turbine compressor.

2.2 Foam production

Foams are used for thermal and sound insulation as well as cushioning and can be distinguished by the composition (chemical substance) and the properties (rigid, flexible). Depending on the type of foam and its application, several different blowing agents and/or propellants are being used.

2.2.1 PU foams

Polyurethane is generated in the reaction of isocyanate with polyol and forms a foam if gas bubbles are forming in the polymerising mixture. The blowing agent can either be formed by a chemical reaction of water and formic acid with isocyanate or by a physical reaction of an inert substance with a low boiling point that generates gas during the polymerisation.

For the latter, CFC-11 was the ideal solution since it was available at low cost and was non-toxic and non-flammable. Low ODP alternatives were selected in the search for substitutes for CFC11: HCFC-141b, HCFC-22 and blends thereof.

Zero ODP substitutes are HFC-134a, HFC-152a, HCs, CO_2 and are commercially available and feasible depending on the application. The fluids HFC-245fa, HFC-365mfc are scheduled to become available in the near future - though their price will be of critical importance for their acceptance in the market.

2.2.1.1 Rigid PU foam

Rigid PU foam is used for the construction of insulated containers such as refrigerators, freezers, picnic boxes, water heaters, insulation panels for construction, pipe insulation and one component foam.

For the use of container insulation, HCFC-141b is the main replacement for CFC-11 as a blowing agent since it can be used as a drop-in replacement. For the future it is expected that HCFC-141b will be partly replaced with HFC-245fa and HFC-365mfc [UNEP, 1998b]. The replacement options HC and CO_2 are expected to compete with the HFC options.

For applications, in which the thermal conductivity is not of major importance, chemically generated CO_2 can be used as a blowing agent. To improve the insulation properties, a physical blowing agent can be added.

In Germany, already 90% of the rigid PU foam production uses the low-GWP and zero ODP HC pentane. The low price of the blowing agent pays off the high investments in conversion of the processing facilities to account for the flammability of the blowing agent [Öko-Recherche, 1999]. In several countries, there is also a reclaim system for decommissioned refrigerators/freezers. One component foam is used in construction and Do-It-Yourself in form of small spray containers, which contain a pre-polymer mixture, that cures under the influence of air humidity. The foam is used for sealing gaps, installing doors and windows,

for sound- and draft-proofing by spraying it into the cavities, where it cures within a day. The traditional blowing agent for this application was CFC12 and has been replaced by other physical blowing agents like hydrocarbons, HFC-134a, HFC-152a and dimethyl ether. Since the content of the spray container is usually applied at once and in closed rooms, the content of flammable fluids has to be limited, e.g. by blending HFCs in with the blowing agent.
Rigid foam can also be generated for in situ application by blending pressurized isocyanate and polyol short before spraying them onto the surface where the foam is needed. This technology is mainly applied in roofing insulation of residential and commercial buildings (especially in North America), tanks, piping and ductwork. The CFC replacements in this application are mainly HCFC-141b and CO2, since flammable substitutes cannot be accepted.

2.2.1.2 Flexible PU foam

Flexible PU foam covers both polyether and polyester-based foams with additives to improve the flammability characteristics. Two types of blowing agents can be distinguished: chemical and auxiliary physical blowing agents. The blowing agents are generated in the curing process during the reaction of the components or added under pressure before curing.
CO_2 is a physical blowing agent generated in the reaction between isocyanate and water. CFC11 used to be the dominant auxiliary physical blowing agent. Several replacements have been found with different characteristics: Methylene chloride, Acetone, Pentane, liquid CO_2
The function of CFC as a foam softener can be replaced by changed chemistry of reactants, e.g. additives.

2.2.1.3 Integral skin

Skin on flexible PU foams is used in many applications such as shoe soles, interior and exterior parts in automotive etc. The skin on the outside of the moulded foam can be generated by controlled condensation (cooling) of the blowing agent before the curing of the foam or by overpacking the mould. The blowing agent for this needs to have a dew point close to ambient temperature, which made CFC11 popular for this application.
Alternative blowing agents for this application are treated in the previous section on flexible PU foams. An additional alternative is the production of the skin with a PVC material and using H_2O as blowing agent.

2.2.2 XPS foams

Extruded polystyrene foam is produced by extruding and heating polystyrene resin to a gel into which the blowing agent is injected and dispersed. The mixture is released into atmospheric pressure through a jet so that the evaporating blowing agent produces a foam. Thin sheets are created by an annular die and cutting the tubular sheet and can be used for packaging after thermo-forming the desired shape of container. Insulation boards are created with a rectangular nozzle.
When the process was invented in Sweden in the 1940s, methyl chloride was used as a blowing agent. Process modifications and progress introduced CFC-12 as blowing agent which has been dominant (>85 %) prior 1986.
Due to the closed cell structure, the greatest part of the blowing agent remains in the cells. Therefore, there is a large amount of CFC still in the installed and disposed XPS foams. So far, there is no reclaim system which guarantees the destruction of XPS with CFC blowing agent after use.
A wide range of alternative blowing agents has been examined and several feasible alternatives have been identified: CO_2 is used, while nitrogen has been found unsuitable since

N_2 is insoluble and produces foam which is not dimensionally stable. HFCs have good physical and chemical properties, but the cost is higher than that for HCs. HCs produce good quality foam and are low in cost. However, their flammability and the VOC regulations in some countries require capital investment. Few manufacturers make use of a CO_2/HC blend [UNEP, 1998e].

For insulation purposes, HCFC blends and HCFC-142b are still the first choice despite their ODP because of their thermodynamic properties. Several alternatives are considered for this application: HFC-134a is a substitute in a limited range of applications due to limited solubility and high price. HFC-134 delivers better solubility but also better diffusion through XPS which makes a higher and consequently more expensive input of blowing agent necessary. HFC-152a features good physical properties alone or in blends with HFC-134a. Its GWP and flammability reduce the application potential. Blends of HFC with CO_2 reduce the cost for the blowing agent and reduces the GWP of the HFCs. Blends of CO_2 with HCs can be used as blowing agents for a wide range of product properties, but the reduced insulation capacity (by 10-15%) and the flammability are characteristics that need to be taken into account. CO_2 is already commonly used in some manufacturers' plants although its poor solubility and decreased insulation values (10-15% lower than HCFC) are disadvantages.

2.2.3 Polyolefin: PE and PP foams

Polyolefin foams are produced in an extrusion process similar to XPS. The blowing agent used to be CFCs which has been substituted by HCFC-142b and blends of HCFC-142b/22. HC are a suitable zero ODP alternative when the removal of the flammable gases is ensured in the production process. HCs are volatile organic compounds (VOCs) and their emission is regulated in some areas.

CO_2 and nitrogen and other inorganic gases have proved to be unsuitable for the use as blowing agent on polyolefin foams.

2.2.4 PIR

Polyisocyanurates produce a rigid foam with good insulation properties, especially when blown with CFC-11. Compared to PU and polystyrene foams, the foam is more resistant to flammability which makes it the choice for sensitive applications where insulation is required. HFC-141b is used a a transitional alternative and the non-ODP alternatives are HFC245fa HFC-365mfc Cyclo/isopentane blends. Flammable blowing agents increase the flammability of the foam.

2.2.5 Phenolics

Phenolic foams have experienced an increase in demand as insulation material due to their fire-resistant properties after the introduction of technologies to produce closed-cell foams with insulation qualities similar to other foams. Historically, mainly CFC-11 has been used as blowing agent. Only a small part of the blowing agent is emitted during manufacture, the larger part is emitted over the lifetime and in the destruction of the product. Present technologies have converted from CFC to HCFC-141b and HFC-245fa is examined as an alternative for the future. Blending small amounts (<8% by weight) of HC into the HFC is considered to improve the efficiency of the blowing agent without reducing the fire resistance. The use of pure HC as blowing agent is seen critical with respect to flammability and in the existing and upcoming regional legislation on VOC emissions as well as under the view of

reduced thermal insulation properties. 2-chloropropane is considered as a suitable alternative since it is not a controlled substance under the Montreal protocol [UNEP, 1998b].

2.3 Solvents

CFC-113 and 1,1,1-trichloroethane were used for degreasing on a large scale prior to 1990. Other uses include the cleaning of electronics from flux residues after printing circuits, precision cleaning or textile cleaning. Other solvents used widely are carbon tetrachloride, HCFC-22, -123, -141b and -225 [UNEP 1998e].

In some applications HCFC-141b is used as an alternative for CFC-113 in degreasing, electronics and precision cleaning despite its significant ODP. Other alternatives are HFC-4310mee, PFCs and other halocarbon solvents.

Non-halocarbon alternatives include aqueous cleaning, HC solvents, volatile methyl siloxanes or changes in the production process to avoid cleaning steps [Kroeze, 1995]. Emission abatement options include ultrasonic cleaning, the recondensation of solvents after their evaporation from the process residues and from the exhaust air and the post-combustion of exhaust air for destruction of the contained solvents.

2.4 Aerosol application

2.4.1 Household products

At a very large scale sprays for all sorts of applications have used CFC-11 as propellants prior to the Montreal protocol. These propellants were replaced with other propellants or NIK technology. Examples for alternative propellants are HC, ether, HFC, N_2, compressed air. NIK alternatives are e.g. pump sprays or roll-on systems.

2.4.2 Medical products

Several drugs can only be delivered to the lungs of patients with the aid of inert propellants in metered dose inhalers (MDIs). Development and testing of alternatives is a very time-consuming task especially when all health risks have to be considered. Consequently, still a good share of these products use CFCs as propellant. Alternative propellants which are considered are HFCs and N_2. Nebulizers or dry powder inhalers (DPI) are an option for some applications, where patients' breathing ability is not limited. Due to companies' price policies, price differences between MDIs and DPIs vary greatly for different countries and specific drugs [Harnisch and Hendriks, 2000]. Enviros-March (2000) have given an overview of uses of MDIs and reduction options and tentative estimates of associated costs.

2.4.3 Technical aerosols

Technical aerosols are another field in which fluorocarbons continue to have critical applications. Nowadays, HFC-134a is the propellant of choice for products that must be non-flammable, e.g. for de-dusters used for electronic equipment. Another example of HFC use based on a technical requirement is non-flammable, long reaching insecticide products used on high-voltage power lines and transformers. HFC-152a is the propellant of choice in some applications where hydrocarbons and dimethyl ether are too flammable but the flammability of HFC-152a is acceptable. HFC-134a and HFC-152a are the propellants of choice for laboratory, analytical, and experimental uses where chemical properties are important and flammability may be a concern [IPCC, 2000b].

2.5 Primary aluminium production

Emissions of perfluorocarbons from primary aluminium productions occur during an intermittent period of the electrolytic process when the cryolithe (Na_3AlF_6) melt becomes depleted of alumina (Al_2O_3) which is the agent to be reduced by means of electric current [IEA GHG, 2000a]. Under these circumstances reactive fluorine forms and reacts with the carbon anodes to form different PFCs such as CF_4, C_2F_6 and C_3F_8 [Harnisch, 1997]. The specific amount of PFCs emitted per ton of aluminium produced mainly depends on the mean frequency and the duration of anode effects per smelter as well as the effectiveness of subsequent post-combustion of anode gases which is applied in most smelters using the Søderberg-Technology. The actual specific emissions are linked to the applied anode technology, the feeding technology, the sophistication of process control, the quality of raw materials, constancy of power supply and the skill of pot room workers and operators. It is can thus yield grossly incorrect results if default emission factors are used for certain production technologies. Short term measurements of PFC emissions from smelters may as well not be representative of annual emissions if operation conditions are changed. Different default emission factors for the technologies in use have been derived and can be used to estimate emissions [e.g. IPAI, 1996; Harnisch et al., 1998; IPCC/OECD/IEA, 1999]. It is current best practise to correlate measured emissions with total anode effect duration (mean frequency × mean duration) and then use this coefficient for recorded or new data on anode effect occurrence. The coefficient is specific for any given smelter and variable in time, but IPCC has developed default coefficients for different technologies as it is currently too costly to permanently measure PFC emissions from a smelter. Emission reductions can be accomplished by smelter conversion, retrofitting, improved plant operation [e.g. Harnisch et al., 1998] or closure of smelters.

The emission in these processes can be reduced by moving to the process with the least emissions, by reducing the frequency and duration of anode effects with automated control and improved feeding technologies. In the case of Søderberg plants, improved gas collection efficiency and improved efficiency in the destruction of PFCs in post combustion flames can also contribute. In the long run so-called inert anodes may also offer a pathway into aluminium production free of PFC emissions. The need for primary aluminium production can be reduced with higher recycling rates and the use of secondary aluminium that has the same properties as primary aluminium.

2.6 Semiconductor production

The use of PFCs, HFCs, SF_6 and NF_3 is common in the production of semiconductors. Two processes are the main sinks for these chemicals: cleaning of CVD (chemical vapour deposition) chambers and dry etching procedures. Both procedures operate based on the same principle of removing Si by the use of a F-containing plasma. This plasma can be created by a large variety of chemicals containing fluorine, e.g. PFCs, SF_6, HFCs or NF_3. 75% of F chemicals are used in chamber cleaning, 25% in etching [Öko-Recherche, 1999]. Other sources give a similar range: [Harnisch and Hendriks, 2000] give values of 70 and 30% respectively.

Deposits of silicon and its compounds in CVD chambers are removed by plasma discharge, which dissociates the molecules of the cleaning agent to produce fluorine. This fluorine reacts with the silicon and silicon dioxide to volatile silicon, which can be removed easily. Since only part of the cleaning agent reacts with silicon, a part of the recombined chemicals is released unaffected. The toxic contents NF_3, F_2, SiF_4 and HF of the exhaust gas are cleaned in a wet scrubber system forming hydrofluoric acid.

The use of the alternative cleaning agent NF_3 would result in emission reductions of 99% in terms of CO_2 equivalent. Old systems, however, cannot be easily converted to new cleaning agents. Due to the short technology cycles and strong growth of production in semiconductor manufacturing, it is expected that 90% of the CVD chambers in 2010 will be from 2000 or younger [Harnisch & Hendriks, 2000].
The second application in semiconductor production is plasma etching. HFC-23, SF_6, are subjected to high-frequency waves to produce F-radicals in a plasma. The radicals create microscopic structures in thin silicon- or tungsten-containing layers by reacting with the layer material and producing volatile fluorides which are extracted from the chamber with the exhaust [Öko-Recherche, 1999].

2.7 Magnesium production and casting

SF_6 serves as blanketing gas during the process of smelting and casting magnesium. SF_6 has replaced SO_2 in this application since the toxic properties of SO_2 affected occupational health. SF_6 reacts on the surface of the molten Mg with the metal and produces a thin crust of MgO and MgF_2 which separates the oxygen from the molten metal. The concentration of SF_6 in CO_2 or dry air is as low as 1%, and only a minuscule proportion participates in the chemical reaction, so that basically all used SF_6 can be considered as emission.
The market for magnesium casting is expected to rise with the growing efforts to reduce vehicle fuel consumption in lowering the vehicle weight by using lighter materials. SO_2 has been used before the introduction of SF_6 and could be used again provided that its concentration in the working environment can safely be kept at an acceptable level. In a large smelter in Norway this conversion back to SO_2 has recently been completed.
Palmer (1999) reports that average usage of SF_6 per ton of processed magnesium varies widely from company to company within a range 0.1-11 kg per ton. Öko-Recherche (1996) suggests that with modification in the furnace design and casting process the emission can be reduced by a factor of 10.

2.8 Production and use of gas insulated switchgear

SF_6 is used in high voltage switch gear because of two properties: SF_6 insulates 2-3 times better against electrical discharges than air under atmospheric pressure, at pressures of 10 bar, the insulation properties are 10 times better. It also reduces the temperature of the electric arc in switching processes because it dissociates at 3,000°C with thus absorbing energy from the arc, which is at temperatures of 7,000°C. This way SF_6 helps to quench arc discharges in high voltage switches.
Typical applications of SF_6 in high voltage technology comprise Gas Insulated Switchgear (GIS), circuit breakers and Gas Insulated Lines (GIL). The former is the globally dominant use of SF_6 in this sector. The later two applications exhibit many similarities with GIS in respect to gas handling and have thus not been covered separately in this study.
Significant emissions already occur during the manufacturing and testing of GIS when the systems are repeatedly filled with SF_6 and re-evacuated. Historically these emissions have been in the range of 30-50% of the total charge of SF_6. The existence and appropriate use of state-of-the art recovery equipment can help to reduce these emissions down to at least 10%.
Losses also occur irregularly during maintenance operation or due to malfunction. If no malfunction occurs, the maintenance interval can be as long as 20 years. Most manufacturers guarantee losses of less than 1% per year, although in practice the leakage rates are below 0.5%. Maintenance often includes the removal of the insulating gas by suctioning it off the switch gear, filtering and reusing the gas for the filling after maintenance. The remaining

amount emitted to the atmosphere depends on the end pressure of the suction pump, typically this is 50mbar.
Recovery of SF_6 from switchgear at the end of the lifetime is equivalent to maintenance. Lifetimes are usually in the order of 40 years, so that decommissioning of the first installed systems will not occur before 2010. Switchgear is traded world-wide and although installation and initial filling with gas is done by qualified experts, there is no reliable international system for SF_6 recovery in the processes of maintenance and decommissioning.
Alternatives for the use of SF_6-insulated switch gear are the installation of comparably large open-air switching facilities. Air insulation properties are up to a factor of 10 lower than of SF_6, which makes larger installations necessary. In addition to this, the switching process produces noise and metal vapour emissions which are not acceptable in densely populated areas. To a limited extend SF_6/N_2-mixtures can be used as an option to reduce the SF_6 charge in GIS and GIL (not applicable to circuit breakers). Another alternative for SF_6-insulated switch gear up to 70kV could be vacuum insulation, at higher voltages, this technology is not acceptable due to the high emission of gamma radiation (x-rays) [Öko-Recherche, 1996].

2.9 Other uses for SF_6

SF_6 in soundproof windows

Due to the low speed of sound in SF_6 (130 m/s), its use recently gained some popularity in insulating double-pane windows in some countries like Germany, Austria and Switzerland. Compared with air or noble gas filled space, the noise transmission is reduced by 2-4 dB. However, the thermal insulation properties are not as good as with air or Argon.
Emissions occur in the manufacturing process, [Öko-Recherche, 1999] states that 30-60% with an average of 50% of the fill is emitted during filling. During the use phase of 20-30 years, is assumed to be 1% per annum. Due to a lack of a recycling scheme, the remaining charge is emitted on decommissioning of windows after a usage time of 25 years. End-of lifetime emissions are expected to occur mainly after 2000 because the first soundproof windows were installed in 1975.
Alternatives to SF_6 filling are cast resin compound glass, different window design e.g. increasing the glass thickness or the inter-space. Emissions can be reduced in manufacturing, when overfilling is avoided and overflow is reclaimed. End-of-lifetime emissions can be avoided by introduction of an effective reclaim system.

SF_6 in car tyres

SF_6 is used in a share of care tires by some manufacturers (especially in Germany) and in the tire trade especially on sports and luxury cars. The large molecules diffuse slower from the car tire than air which provides improved pressure stability. There is no existing system to reclaim the 250-350g SF_6 per tire after the average tire lifetime of 3 years.
One alternative offered by the tire trade is the filling with pure nitrogen. The return to air as filling gas can be seen as an alternative although a comfort penalty has to be accepted [Öko-Recherche, 1999].

SF_6 in sport shoes and tennis balls

SF_6 is also used in training shoes and tennis balls because of the low diffusion rate through the polymer material which leads to longer resilience of the product. Nitrogen and other non-GWP gases can be used as alternatives without great reduction in product life expectancy if e.g. special coatings which reduce the diffusion rate are used. Currently, the use in these applications is phased out [March, 1999].

SF_6 in electronic equipment

SF_6 is used in several electronic devices in which high voltages have to be insulated in little space:

- particle accelerators
- electron microscopes (with acceleration voltage >200kV)
- X-ray material testing
- X-ray linear accelerator for medical therapy
- AWACS radar

SF_6 as tracer gas in atmospheric research

SF_6 can be detected in extremely low concentrations and is chemically stable, so that atmospheric air flows can be detected. This is used in small range applications to evaluate cold air dispersal, fresh air passages etc. as well as in long range applications for landfill and sewage plant design, testing of impact of nuclear explosions, atmospheric flow research etc.

Degassing of Al melt before casting

In secondary and primary aluminium smelters, a number of different fluids are used to remove hydrogen, alkali metals, alkaline earth metals and solids. Primary smelters often use elementary chlorine, most secondary smelters use nitrogen and/or argon. Few smaller secondary smelters and research facilities use inert gas with 1-2.5% SF_6 content [Öko-Recherche, 1999].

2.10 By-product emission from HCFC production

HFC23 is a by-product of the production of HCFC 22, caused by over-fluorination of the process. Depending on the process parameters, the specific formation rate commonly varies between 1.5 and 4% if no abatement is carried out [Branscome and Irving, 1999].

The most important abatement option is the collection and destruction of the concentrated HFC23 e.g. by thermal oxidation. The products from this process need to be treated and fluoride may be recovered for recycling in the process [Harnisch and Hendriks, 2000].

2.11 Manufacturing and distribution losses

As pointed out by Gamlen et al. [1996] and Midgley and McCulloch [1999] diffusive losses of about 2% commonly occurred for chlorofluorocarbons (CFCs) during manufacturing and packaging. Recent work by the IPCC/IEA/OECD Greenhouse Gas Emission Inventory Programme suggests that distribution losses account for another 2%. There is some indication that respective loss rates associated with manufacturing, packaging and distribution are currently decreasing for HFCs due to improved handling equipment and procedures.

2.12 Industrial products

A number of industrial products are produced with the use of ODS process agents and feedstock. UNEP [1997] mentions typical uses for process agents and feedstocks as given in Table 4.

Table 4 Typical uses of ozone depleting substances as process agents and feedstocks

ODS	Process	Product use	Non-ODP alternatives
CTC	removal of NCl_3 impurities in Chlorine	production of chemicals, polymers, solvents and pharmaceuticals	elimination of N-compounds from brine, destruction of NCl_3, use of very pure salt
CTC	Caustic Soda	paper production	
CTC	Chlorinated Rubber	heavy duty anti-corrosive and adhesive, motorway marking paint	aqueous process
CTC	Endosulphan	Insecticide-acaricide	other solvents
CTC	Ibuprofen	pharmaceuticals	Ethylene Dichloride
CTC	Dicofol	Acaricide	Chlorinated aliphatic solvents
CTC	Chlorosulphonated polyolefin (CSM)	automotive belts and hoses, cable and wire insulation, gaskets, rafts and rescue boats	Chlorobenzene
CTC	PPTA polymer	armour, helmets, containers for dangerous goods	
CTC	Styrene Butadiene Rubber		
CTC	Chlorinated Paraffin		
HCFC-22	Monomer Tetra-fluoroethene for Fluoropolymers	PTFE as basic high performance polymer for technical and consumer appliactions	
CFC-113	Fluoropolymers resins	cable and wire insulation, coating for cookware	HC solvents, other processes
CFC-11	Fine synthetic fibre Sheet structure	Packaging, protective clothing, air infiltration barriers	available, but not specified
1,1,1, Trichlorethane	HCl	generation of high grade HCl for semiconductor manufacture in diffusion furnace	1,2 trans-DCE, Methylene chloride
CFC-12	graphite	generation of high grade graphite for graphitisation	HFC-134a

2.13 Fire fighting

Halon-1211 and halon-1301 have been applied widely for fire extinguishing equipment, halon1211 mainly in portable and halon-1301 in fixed flooding systems. Some applications also used halon-2402 in the former Soviet Union. Halons were also used in explosion protection.

In the use as fire extinguisher, halons are ideal for all fires since they do not leave harmful residues, do not conduct electricity and are not toxic. Most emissions of halons historically occured during testing [UNEP, 1999c].

Alternatives to halons like water-based systems, dry powder, inert gases, CO_2, HFCs and PFCs have displaced 95% of halon uses. The rest of the applications are considered critical with no feasible alternatives: e.g. aircraft, military vehicles, or installations where the risk of fire or explosion would lead to major threat to humans, the environment or national security [UNEP 2000].

2.13.1 Fixed systems

Sensitive systems like computer and telecommunication servers, military or security applications are contained in sealed rooms and equipped with extinguishing systems that floods the room in case of fire. To ensure that staff working in this environment is not harmed, the extinguishing agent has to be non-toxic.
Halons are ideal for this use since they can be applied in large concentrations without causing asphyxiation. In these applications, halons are replaced with HFCs, e.g. HFC-227ea. In applications, where the sensitivity does not allow the change to alternatives, the flooding system is treated with more awareness of the ODP of halons- i.e. discharges for test purposes are reduced to a minimum.

2.13.2 Portable systems

Portable fire extinguishers are used widely and can be chosen according to the nature of the environment and the fires that may occur. Therefore, replacement for halon extinguishers is found easily in CO_2, foam, water or dry powder.

2.14 Methyl bromide

Current knowledge about sources of methyl bromide is characterised by a high level of uncertainty. The anthropogenic sources of methyl bromide are fumigation in agriculture (soils, perishable goods, structures), the combustion of leaded fuel and biomass burning. Natural sources are oceanic production (phyto-plancton etc.), plant, soil and marsh emissions. Sinks are identified in the photochemical decomposition in the atmosphere, in soils, oceans and absorption in plants. Of the 68,666 t used in 1996, 76% were used in soil fumigation, 15% for fumigation of durable commodities and 9% for perishable commodities.
Since the decision to phase-out the use of CH_3Br, research and development of alternatives has grown considerably, but the demonstration and implementation will require several years until results are available on the market.

2.14.1 Fumigation in agriculture

In agricultural applications, methyl bromide is used as a powerful biocide to fumigate soil in order to obtain sterile substrate which is needed to comply with quarantine or pre-shipment regulations or as in most cases to avoid losses in valuable and sensitive crops. There are feasible alternatives to replace 95% of CH_3Br use with non-ODP techniques.
Some chemicals have been found to replace CH_3Br effectively e.g. dichloropropene and chloropicrine. Other alternative chemicals are under examination. In addition to this, other strategies can avoid the use of CH_3Br: integrated pest management (e.g. crop rotation, biofumigation, planting time etc.), biological control (resistant plant varieties, natural predators etc.) physical soil treatment (e.g. with steam or solarisation) and strategic application of selective pesticides.

2.14.2 Treatment of wood, structures and durable commodities

Durable commodities and wood are treated with CH_3Br to eliminate pests and rodents to ensure that they can be stored safely for long periods. 12% of the use are utilised in commodity and 3% in wood and structure fumigation.
For dry commodities, heat, cold, phosphine, contact pesticides and irradiation are feasible and available alternatives, treatment with CO_2, N_2 and inert dust are under consideration and applied in few projects. Heat, sulphuryl fluoride and chemical wood preservatives are alternatives for wood treatment and sulphuryl fluoride and heat are feasible alternatives for the use in structures. Further alternatives are in the research stage.

2.14.3 Disinfecting of perishable commodities

CH_3Br is used for disinfecting perishable commodities to preserve them during the transport and for quarantine purposes to avoid the transfer of pests from the production to the consumption location. About 9% of the global production of CH_3Br is used for this purpose. Heat, cold, irradiation and combinations thereof are alternatives to CH_3Br fumigation already accepted by several authorities and some goods. Chemical fumigation alternatives are available but manufacturers hesitate to invest in the costly registration procedure. Pre-harvest practices may also make the fumigation after introduction of the goods into the destination location redundant.

The diverse characteristics of perishable commodities have to be accounted for by different measures to preserve them. This diverse infrastructure is of course more complicated than the routine use of CH_3Br, especially in quarantine applications where universal methods with short treatment times are preferred. Therefore the reduction potential cannot be quantified precisely.

3 Emission scenarios

The economic evaluation which is part of this project for the IEA GHG R&D Programme requires a dynamic and detailed bottom-up emission model to connect emission projections to reduction options and associated costs. The current knowledge of emission levels for the gases is still fairly limited. There is virtually no database or emission model that would provide a consistent coverage for more than a few compounds. Neither do most existing emission inventories permit to make projections of future emission levels.

Global emission levels of the compounds covered by this study are known from atmospheric observations of individual chemical species [WMO, 1999]. These atmospheric measurements provide little information on the regional distribution of sources and can generally not be used to differentiate emissions from different sectors of the economy or distinct technological processes.

Therefore it was decided to develop an emission model for this study in order to have a consistent and transparent coverage of an extended number of emission sources from various sectors. The model was built for use in policy assessment and not for applications in atmospheric sciences. It thus did not need to have a high spatial or temporal resolution or produce emission data for each individual species. Its main strength is a consistent link between past and future emission levels, a reasonable representation of different technological sectors, a technology oriented link between emission levels and abatement options and - last but not least - a high degree of flexibility for modification of sector specific data like emission factors, growth rates, GWP data and alike.

3.1 General characteristics of the emission model

Fundamentally, the temporal evolution of Emissions in this model is calculated as the product of an emission factor and a technological activity. Both are generally assumed to be time-dependent: the former due to “incremental” technological change (e.g. improved containment of refrigerant) and the latter through economic growth (e.g. increasing demand for domestic refrigeration) or major shifts between technologies (e.g. the switch between different classes of refrigerants).

3.1.1 Sectoral structure

The emission model which was created for this study builds on the experience gained for a recent study for the European Commission (Harnisch and Hendriks, 2000). It covers 22 different sub-sectors that contribute to emissions of the "engineered chemicals" covered by this study.

1. Commercial refrigeration
2. Cold storage and food processing
3. Industrial refrigeration
4. Stationary air conditioning and Heat Pumps
5. Transport refrigeration (road, rail, ship)[3]
6. Heat Pumps (for heating only)
7. Domestic and small commercial (hermetic) refrigeration
8. Mobile air conditioning
9. Extruded polystyrene (XPS)
10. Polyurethane (including one component foams), polyisocyanurate and phenolics
11. Solvents
12. Metered dose inhalers (MDI)
13. Technical aerosols
14. By-product emissions of HFC-23
15. Primary aluminium production
16. Semiconductor production
17. Magnesium production
18. Use of gas insulated switch gear
19. Manufacture of gas insulated switch gear
20. Fire-fighting
21. Soil and fruit fumigation
22. Manufacturing and distribution losses

3.1.2 Regions of the model

Due to the generally poor spatial resolution of available use and emission data for most processes covered by this analysis it was decided to build it around only four major regions:

1. North America (USA and Canada)
2. Western Europe (European Union (EU-15), Norway, Switzerland, Iceland)
3. Japan
4. Rest of World[4] (thus: Latin America, Oceania, Africa, Asia (excl. Japan), the Commonwealth of Independent States and the Eastern European Countries in Transition).

These are the same regions used in most of the recent UNEP Technical Options Reports. By using this small number of regions it was avoided to create, use and report so-called "proxy data" for certain regions and countries (e.g. according to their share of gross domestic product of a larger region). Such proxies generally have a significantly higher uncertainty than the

[3] According to UNEP [1998a] maritime sources accounted for 75% of emissions from this sector in 1996.

[4] In terms of reported 1986 consumption of the main chlorofluorocarbons (as ODP-tons) the different regions of Rest of World had the following shares of consumption: Russia (36%), Asia (22%), Eastern Europe (15%), Latin America (12%), Africa (9%), Oceania (6%). It is very likely that by 1996 booming Asia (mainly China followed by South Korea and Thailand) has overtaken even the combined consumption of "engineered chemicals" in economically declining Russia and Eastern Europe. Source: UNEP (1999b).

original values from technology inventories for the four major regions. In the past North America, Europe and Japan together have been responsible for by far the largest share of emissions (>80%) of the "engineered chemicals" with large regions such as China, India or Africa contributing only comparably little despite their large populations.

3.1.3 Time resolution

The model has been designed to derive emission estimates for three years (base year, 2010 and 2020) covering a period of roughly 25 years. As the base year is close to the present, the year 1996 was selected for which data coverage by the UNEP Technical Options Reports is most complete for almost all processes in which ozone depleting substances have been used in the past. In a few instances the years 1995 and 1997 had to be used as the base year in certain sectors due to the lack of data for 1996. The resulting error, however, is very minor compared to the overall uncertainties of emission estimates in this field.

3.1.4 Emitted compounds

In many sectors covered by this study (e.g. in refrigeration) a large number of different compounds is used. These compounds are here aggregated into a small number of substance class (HFCs, HCFCs, CFCs, PFCs, SF_6, methyl bromide or halons) in order to limit the complexity of the model. For a number of compounds covered by this study, data on annual production and sales of fluids into broad market categories are available, e.g. AFEAS [1998]. However, this information is of limited value to directly constrain future emission estimates as most relevant markets will remain in a state of rapid transition between specific substances for an extended period of time.

It is tried to reflect the specific mix of compounds in each sub-sector by estimating an appropriate value for the mass-weighted global warming potential of fluids used. These mean GWP values are assumed to remain constant in time per application and substance class which will obviously be only a first approximation of the real evolution (Annex III Calculations and data tables). For a number of applications the choice of this mean-GWP is particularly uncertain as it is undetermined which effective mix of HFCs is going to be used in this sector: e.g. in technical aerosols and extruded polystyrene HFC-134a or HFC-152a with GWP-values of 1500 and 160, respectively (the model assumes a constant 830 over time).

3.1.5 The reference scenario, emission factors and uncertainties

The reference scenario which is calculated for the years 2010 and 2020 is set up to make conservative assumptions about technological progress, i.e. it avoids reliance on large autonomous emission reductions without a corresponding regulatory framework. In regions in which companies in their actions already anticipate future regulation on greenhouse gas emissions[5] this might lead to an overestimate of future emissions. As a result e.g. in the case of Europe, derived reference scenarios from this study result in higher projected emission levels than analyses specifically dedicated to the European Union like March [1998] and Harnisch and Hendriks [2000].

The choice of present and future emission factors is based on studies like Öko-Recherche [1996], March [1998] and Harnisch and Hendriks [2000]. However, many simplifications had to be made for reasons of practicability and limited data availability. The projected evolution of emission factors in the future was based on expert judgement as internationally no accepted standards exist for this purpose. Resulting uncertainties are evidently fairly large. Assumptions on the evolution of emission factors and the baseline penetration of improved

[5] If however such policies and measures would eventually not be introduced, companies would sooner or later revert to the more emissive technologies of the less costly reference trajectory.

technologies are the main sources of uncertainties. Underlying economic growth scenarios for different regions and applications are generally of lesser importance. With only few notable exceptions, uncertainties of emission estimates and projections will generally be as high as ±50% on a 95% confidence level. This value is limited to estimates of emissions in terms of mass flows of substance. The conversion into hypothetical 100-year carbon dioxide equivalents increases uncertainties significantly especially for the ozone depleting substances.

Annex I Sectoral modelling of emissions in the back of this report describes in detail how emissions are calculated for each of the sectors. In every sector a bottom-up perspective is used to characterise emissions on the basis of underlying technological activities.

3.2 Emissions in 1996, 2010 and 2020 in the reference scenario

This paragraph discusses results for the reference emission scenario produced from the emission model described above. Detailed numerical results per sector are presented in Annex III Calculations and data tables in the back of this study. Figure 4 shows how the contribution of different substance classes is projected to change in time. CFC emissions are found to rapidly decrease in their contribution to global warming while HFCs become increasingly important. The cooling influence of halon emissions vanishes in the time after the year 2000. The relevance of emissions of HCFCs, PFCs, SF_6 and methyl bromide is projected to remain fairly limited in time.

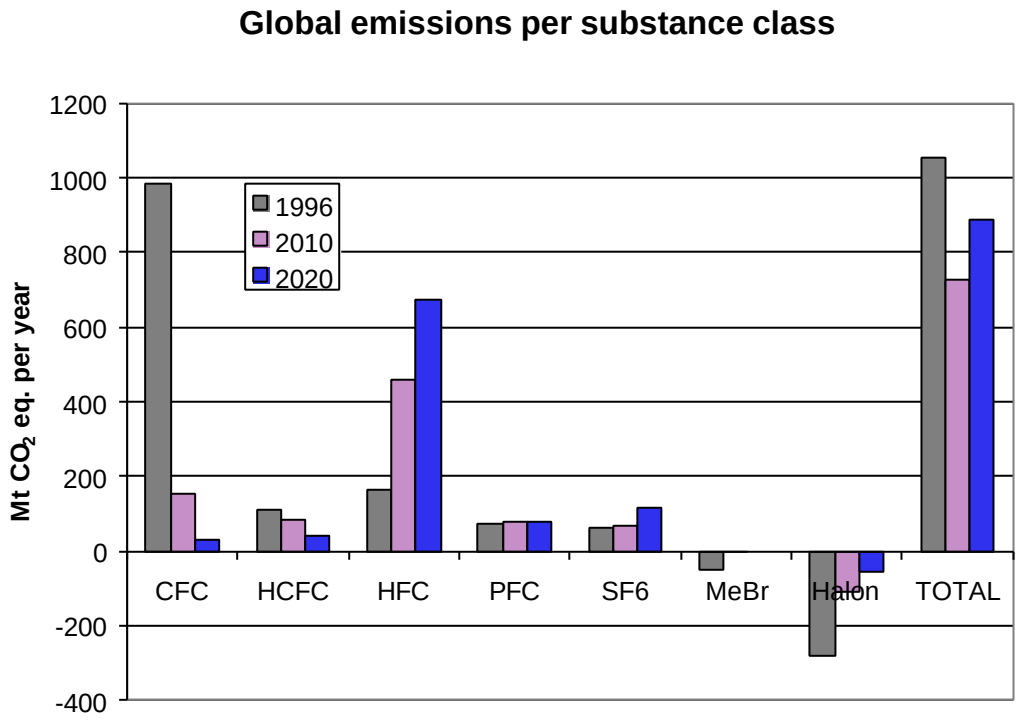

Figure 4 Temporal evolution of global emissions per substance class as CO_2 equivalents

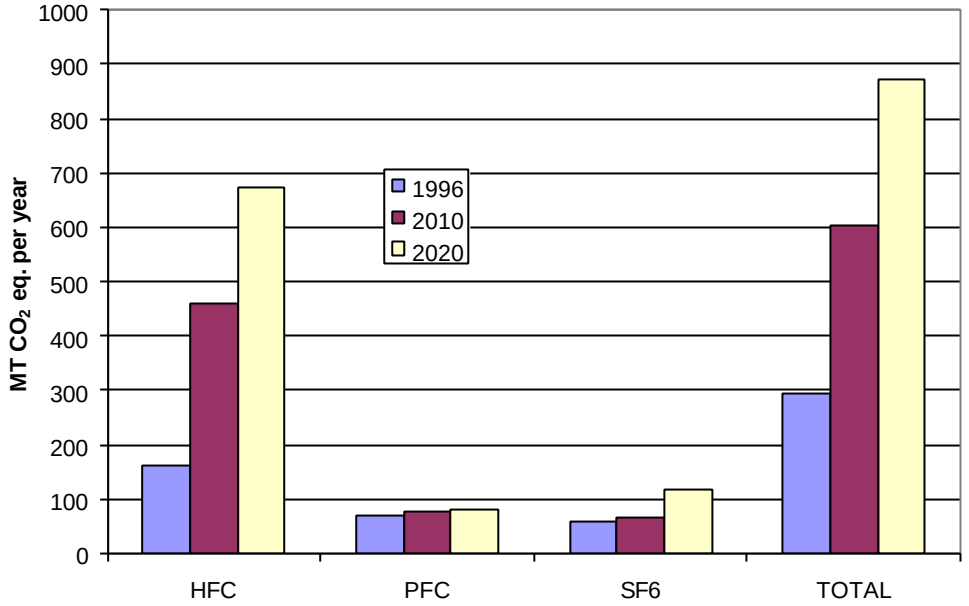

Figure 5 Temporal evolution of global emissions - Kyoto gases only.

The gases regulated under the Kyoto Protocol exhibit a fairly steep increase from 1996 to 2020. They are projected to double between 1996 and 2010 and then grow by little less than another 50% until 2020. Assuming a stabilisation of emission levels of the greenhouse gases in the Kyoto basket at 1995 levels, HFCs, PFCs and SF_6 will globally contribute about 2 % of CO_2 equivalent emissions in 2010 and grow to 3 % in 2020 compared to about 0.9% in 1996.

Figure 6 illustrates the pronounced differences between the four regions covered by this report. While under given assumptions emissions (as CO_2-equivalents) are expected to fall for North America, remain fairly constant for Western Europe and Japan, while Rest of World is projected to exhibit a rapid increase of emission levels. The decline of cooling emissions of halons weighs particularly heavy for Rest of World. This coincides with a rapid growth of emission from a number of sectors. In Figure 7 the global evolution of emissions from the specific sectors is presented in CO_2 equivalents. The dynamic situation for mobile air conditioning, PU/PIR foams and for Fire-Fighting is most striking. Data for key-sectors are presented in an aggregated perspective in Figure 8. The projected break-up for 2020 of the largest sector ("Refrigeration and Air Conditioning") is shown in Figure 9. Stationary sources are projected to dominate mobile source by a ratio of 70:30.

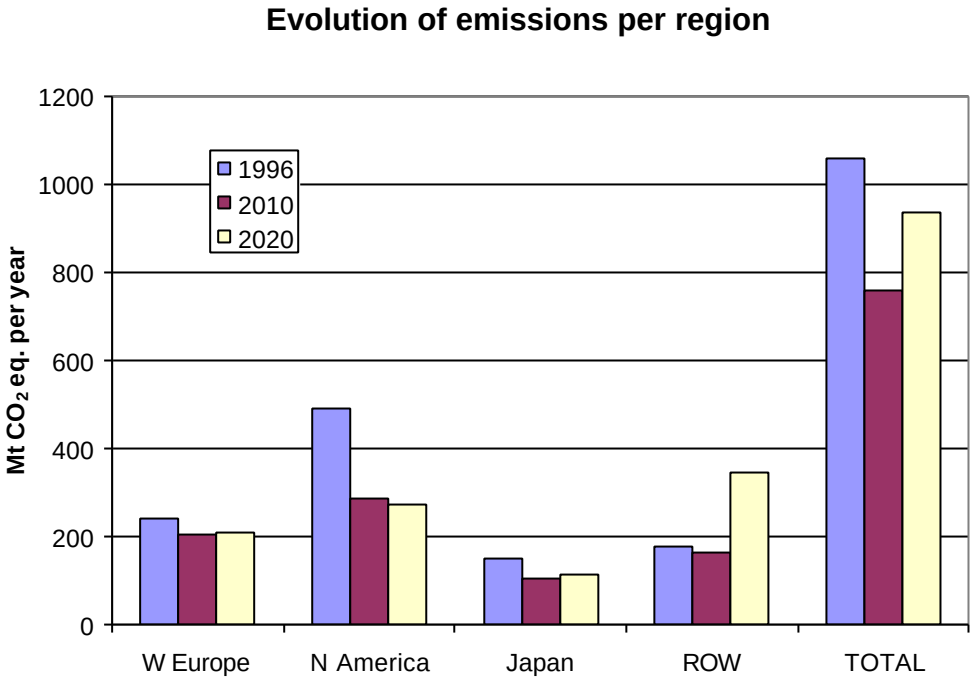

Figure 6 Temporal evolution of global emissions per region as CO_2 equivalents

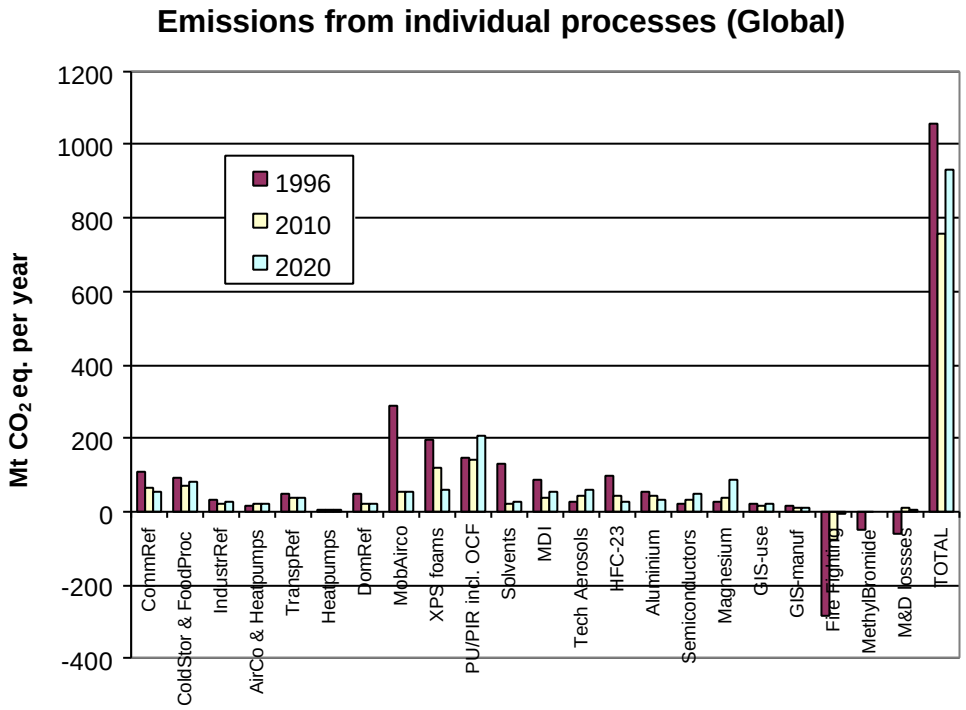

Figure 7 Temporal evolution of global emission per process[6] as CO_2 equivalents

[6] Commercial (supermarket) refrigeration (CommRef), Cold storage and food processing (ColdStor & FoodProc) and general industrial refrigeration (IndustrRef), stationary air conditioning and reversible heat pumps (AirCo & Heatpumps) transport refrigeration including merchant and naval ships (TranspRef) and domestic refrigeration (DomRef), mobile air conditioning (MobAirco), extruded polystyrene foams (XPS foams), polyurethane and polyisocyanurate including one component foams (PU/PIR incl. OCF), metered dose inhalers (MDI), use and manufacture of gas insulated switchgear (GIS), manufacturing and distribution losses (M&D losses).

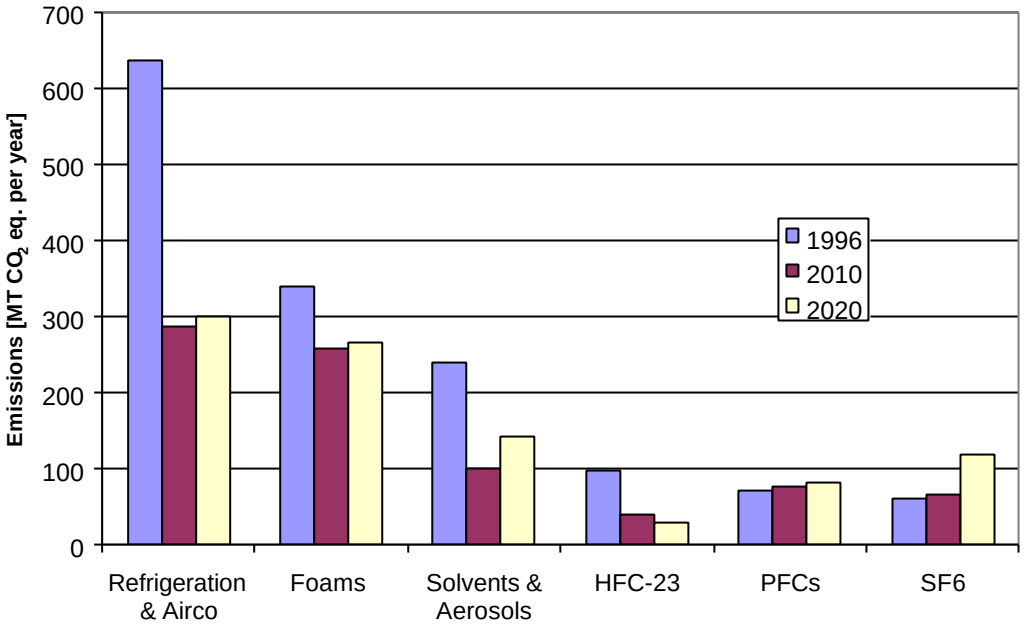

Figure 8 Same as Figure 7 but for aggregated key-sectors.

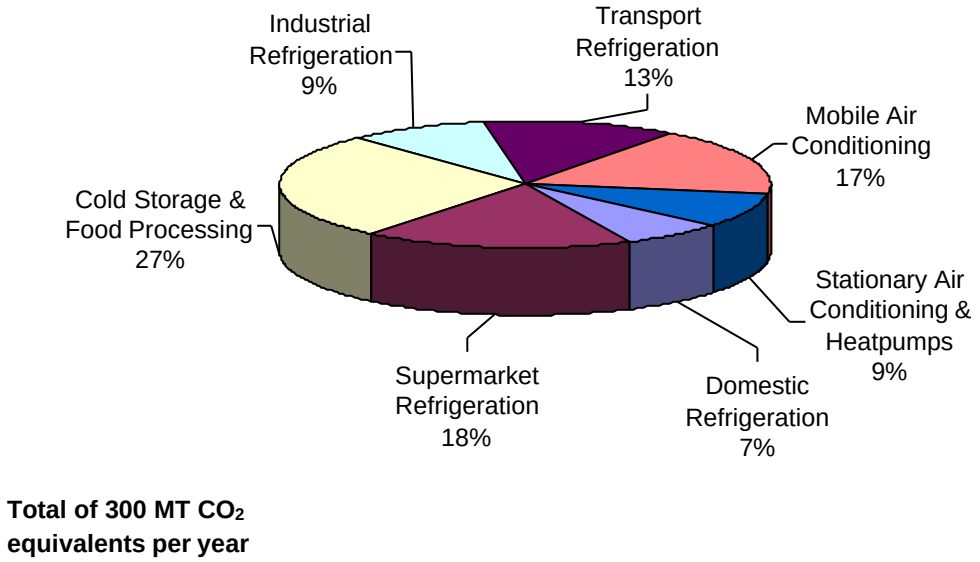

Figure 9 Break-up of emissions from different sub-sectors of refrigeration and air conditioning in 2020.

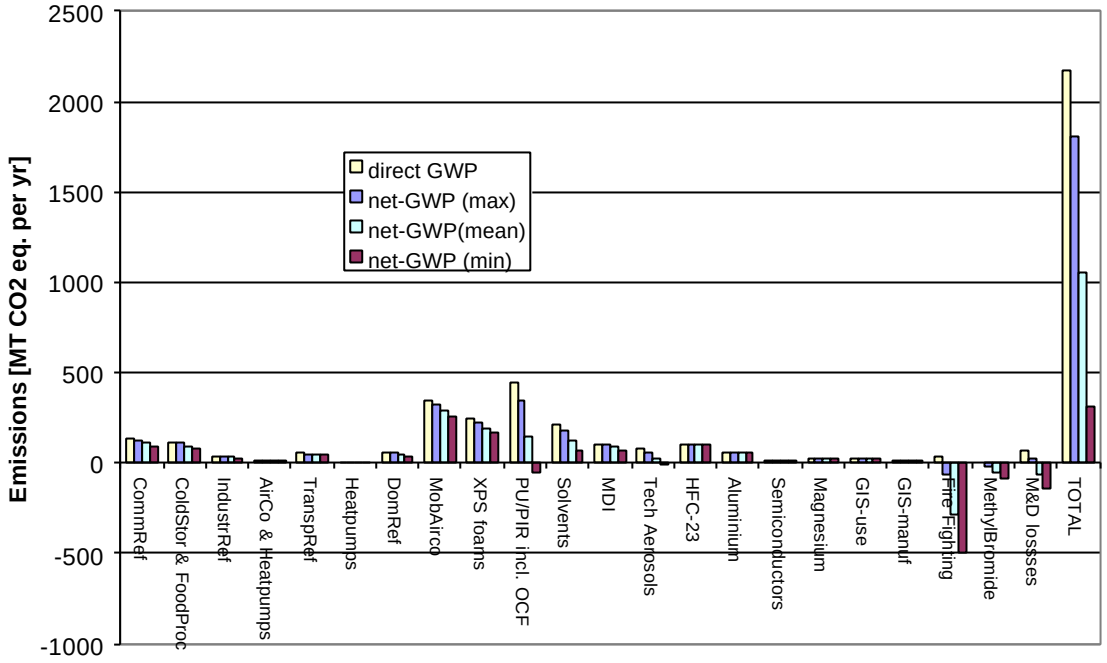

Figure 10 Sensitivity of calculated 1996 emission levels in CO_2 equivalents for processes[6] and different choices of net GWPs.

The significance of the choice of appropriate net-GWPs has already been discussed above. Its impact on overall emission levels can be expected to be largest in 1996 when the emissions of ozone depleting substances (ODS) were still quite significant. Figure 10 illustrates how 1996 base year emissions vary between 300 and 2200 MT CO_2 eq. per year depending on whether minimum, mean or maximum or simply direct GWP-values are taken. In terms of their relative contribution to emissions of CO_2 equivalents this translates into roughly 3 ± 2 % of global emissions of all anthropogenic greenhouse gases in 1996 if at least net-GWPs are considered.

The inclusion of the ODS into these calculations leads large uncertainties of base year emission levels which seem to preclude any meaningful conclusion on whether future emissions in terms of CO_2 equivalents will increase or decrease relative to base year levels.

A look at how emissions of long-lived halogenated compounds evolve in time on a mass basis can therefore be illustrative. It shows that growing emissions from the foam sector are likely to compensate for specific emission reductions in the refrigeration and air conditioning sectors. It should be kept in mind this analysis on a pure mass basis does not capture emissions of alternatives (e.g. in the solvent or technical aerosol sector).

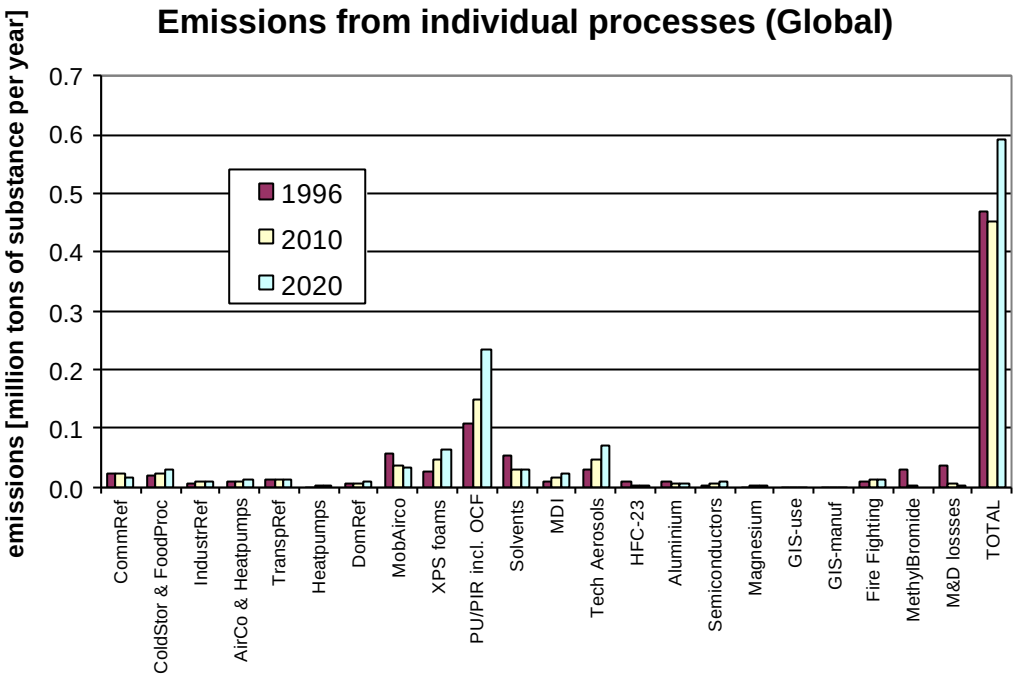

Figure 11 Evolution of emissions in mass units of substance for different processes[7].

3.3 Energy efficiency issues

It is often overlooked that the use and substitution of halogenated compounds is intimately interlinked with energy efficiency issues. One prominent example is refrigeration and air conditioning: Combining our data collected on banked amounts of refrigerants with estimates of specific energy consumption per ton of refrigerant [Harnisch and Hendriks, 2000] permits a rough estimate of energy consumed associated with cooling and air conditioning. We here estimate that in 1996 roughly 0.7 PWh (5%) out of 13 PWh electricity generated globally were consumed for these applications. Applying an emission factor of 0.5 kg CO_2 / kWh yields about 300 MT of associated CO_2 emissions. Mobile air conditioning probably added another 40 MT of CO_2 due to increased energy consumption of vehicles in 1996. Aluminium production and magnesium production which lead to emissions of PFCs and SF_6 contribute at least another 250 MT of associated CO_2 emissions [IEA GHG, 2000b; Harnisch et al, 1998]. The use of halogenated compounds in blowing thermal insulation foams is an example in which these compounds help to conserve energy through reduced need for heating or cooling. Due to the many existing alternative insulation materials and the multitude of applications it is currently not possible to quantify this contribution. Many other examples can be found that suggest that for a redesign of systems / applications involving halogenated compounds one needs to carefully look at associated changes of the energy consumption and associated emissions in order to provide a benefit to the environment. The concept of the Total

[7] Commercial (supermarket) refrigeration (CommRef), Cold storage and food processing (ColdStor & FoodProc) and general industrial refrigeration (IndustrRef), stationary air conditioning and reversible heat pumps (AirCo & Heatpumps) transport refrigeration including merchant and naval ships (TranspRef) and domestic refrigeration (DomRef), mobile air conditioning (MobAirco), extruded polystyrene foams (XPS foams), polyurethane and polyisocyanurate including one component foams (PU/PIR incl. OCF), metered dose inhalers (MDI), use and manufacture of gas insulated switchgear (GIS), manufacturing and distribution losses (M&D losses).

Equivalent Warming Impact (TEWI) has been developed to assess different systems in this respect (see for example Ecofys [2000]).

4 Assessment of abatement and control options

4.1 Costing method

The emission reductions are calculated on an annual basis. All cost data of this report are calculated as 1999 US$. Abatement costs were calculated from the sum of annualised investment costs and annual operating and maintenance costs divided by mean annual emission savings:

$$\text{Specific costs} = \frac{\text{Annualised capital costs} + \text{annual O\&M}}{\text{Annual abated } CO_2 \text{ emission}}$$

The annual operation and maintenance costs were assumed to remain fixed over the depreciation period. The annualised capital costs are calculated by multiplying the total investment with the annuity factor¸ where d = the discount rate (100%=1) and n is the technical lifetime of the measure in years:

$$\text{Annuity Factor} = \frac{d}{(1-(1+d)^{-n})}$$

Investment costs were annualised over their lifetime (here 15 years are used as default value) at a discount rate of 5% per annum which is a value commonly used in a macro-economic analyses. However, this is well below discount rates used for commercial investment decisions (10-30% per annum depending on the specific industry - correspondingly resulting in higher specific abatement costs).

4.2 Consideration of the Montreal Protocol

The reference scenario has been designed under the assumption of full compliance with the Montreal Protocol in all regions. This study was not designed to assess the costs of an accelerated phase-out of ozone depleting substances in one or several regions. Therefore the model permits an emission abatement exclusively of non-ODS comprising the Kyoto-gases: HFCs, PFCs and SF_6. However, it is important to keep in mind that a number of interactions do exist between the transitions under the Montreal Protocol and potential emission reductions under the Kyoto Protocol. For example: Some countries have phased-out ODS several years ahead of other countries. They now operate a large number of processes, e.g. in refrigeration using HFCs as no other alternatives had been available at the time of the transition. And the opposite case: The Multilateral Fund (MLF) grants investment assistance for companies in developing countries only once without explicit consideration of the climate impact of the alternative. Enterprises in developing countries may thus delay a conversion away from ODS in anticipation of changing regulation on HFCs as a consequence of the Kyoto-Protocol. For the purpose of this study it was not attempted to economically capture these effects. Instead a natural turnover of capital was assumed.

4.3 Database

The cost information used in this study is taken from a database created as part of the analysis[8] "Economic Evaluation of Emission Reductions of HFCs, PFCs and SF_6 in Europe" [Harnisch and Hendriks, 2000]. This study is part of the assessment "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change" prepared on behalf of the Directorate General Environment of the European Commission. The study contains a detailed description of most technological abatement options used in this study for the IEA GHG. Notable exceptions are solvents and technical aerosols for which costs estimates from March [1998] and MDI for which costs data from Enviros [2000] were applied. Leakage and recovery in fire-fighting are assumed to exhibit a comparable cost structure like commercial refrigeration. Indicatively, a portion of manufacturing and distribution losses is assumed to be abatable at costs five times the current wholesale price per mass unit of fluid.

Generally, it is assumed that economic and technological conditions across the globe will be comparable to the situation in the European Union. In the short term, this assumption will obviously be violated in many developing countries and in the economies in transition. In the longer run it currently seems very appropriate to assume a continuation of the ongoing economic and technological convergence across the globe.

To limit the complexity of this analysis generally only one abatement option was assigned to each of the 22 sectors modelled[9]. The potential to reduce a share of projected emissions in 2010 and 2020 was estimated and is given in Table 5. Specific investment, operating costs and calculated abatement costs per ton of substance annually not emitted are reported in Table 6.

Based on the experience from the study for Europe often the least cost option among several candidates was selected. Alternatively, a weighted mean from a number of options was calculated to appropriately address different sub-sectors like in the case of the fairly diverse field of polyurethane foam production or for aluminium production.

The selection of a technological option is not intended to be prescriptive. It is fully recognised that a tremendously dynamic process of research and development is currently reshaping many of the sectors studied. Frequently, new approaches nowadays marginalise what seemed to be a dominant technologies. With a timeframe of 20 years ahead, many of the proposed abatement options can only be intended as "backstops" i.e. giving an indication that the final technical solution cost will exhibit equal or smaller costs than the proposed approach.

[8] Can be downloaded from the website of the European Commission at:
http://europa.eu.int/comm/environment/enveco/climate_change/emission_reductions.pdf

[9] As neither methyl bromide emission nor its replacements are regulated under the Kyoto Protocol, no respective cost data were collected for process 21.

Table 5 Key abatement options for processes and associated maximum emission reduction rates in 2010 / 2010 and associated specific costs (per ton of substance).

Code #	Process	Abatement option	Maximum reduction in 2010 [%]	Maximum reduction in 2020 [%]
1	Commercial Refrigeration	Leakage reduction & recovery	30	60
2	Cold Storage & Food Processing	Alternative Refrigerants	50	90
3	Industrial Refrigeration	Alternative Refrigerants	50	90
4	Air Conditioning & Reversible Heat Pumps	Leakage reduction & recovery	40	80
5	Transport Refrigeration (Road, Rail, River, Sea)	Leakage reduction & recovery	40	80
6	Heat Pumps	Leakage reduction & recovery	40	80
7	Domestic Refrigeration	Hydrocarbons	60	100
8	Mobile Air Conditioning	Alternative Systems	25	100
9	Extruded Polystyrene Foams	Carbon dioxide	50	80
10	Polyurethane Foams including One Component Foams	Hydrocarbons	50	80
11	Solvents	Process Modifications	20	40
12	Metered Dose Inhalers	Dry Powder Inhalers	50	70
13	Technical Aerosols	Non-in-kind & Low GWP	0	0
14	By-product HFC-23	Thermal Oxidation	90	90
15	Aluminium	Retrofitting	20	40
16	Semiconductors	NF_3 / alt.chem / Thermal. oxidatn	70	100
17	Magnesium	SO_2 cover gas	70	90
18	Gas Insulated Switchgear- use	Leakage reduction & recovery	30	60
19	Gas Insulated Switchgear- production	Improved recovery	30	60
20	Fire Fighting	Leakage reduction & recovery	30	60
21	Methyl Bromide	Replacements	0	0
22	Manufacturing & Distribution Lossses	Process Improvement	30	60

Table 6 Key abatement options for processes, specific investment, specific operating, and specific calculated abatement costs[10] (per ton of abated substance).

Process	Abatement option	Investment cost [US$(99) / ton substance	Operating cost [US$(99) / ton substance	Abatement cost [US$(99) / ton substance
1. Commercial Refrigeration	Leakage reduction & recovery	249000	125000	149000
2. Cold Storage & Food Processing	Alternative Refrigerants	402000	-30000	9000
3. Industrial Refrigeration	Alternative Refrigerants	400000	-30000	9000
4. Air Conditioning & Reversible Heat Pumps	Leakage reduction & recovery	100000	63000	72000
5. Transport Refrigeration (Road, Rail, River, Sea)	Leakage reduction & recovery	81000	81000	89000
6. Heat Pumps	Leakage reduction & recovery	100000	63000	72000
7. Domestic Refrigeration	Hydrocarbons	49000	0	5000
8. Mobile Air Conditioning	Alternative Systems	365000	0	35000
9. Extruded Polystyrene Foams	Carbon dioxide	12000	6000	7000
10. Polyurethane Foams including One Component Foams	Hydrocarbons	22000	11000	13000
11. Solvents	Process Modifications	300000	0	29000
12. Metered Dose Inhalers	Dry Powder Inhalers	0	533000	533000
13. Technical Aerosols	Non-in-kind & Low GWP	21000	4000	6000
14. By-product HFC-23	Thermal Oxidation	16000	1000	3000
15. Aluminium	Retrofitting	104000	-20000	-10000
16. Semiconductors	NF_3 / alt.chem / Thermal. oxidatn	363000	219000	254000
17. Magnesium	SO_2 cover gas	99000	0	10000
18. Gas Insulated Switchgear- use	Leakage reduction & recovery	238000	71000	94000
19. Gas Insulated Switchgear- production	Improved recovery	40000	12000	16000
20. Fire Fighting	Leakage reduction & recovery	249000	125000	149000
21. Methyl Bromide	Replacements	-	-	-
22. Manufacturing & Distribution Lossses	Improved handling	0	20000	20000

[10] Negative operating costs are a result of reduced energy consumption. Negative abatement costs correspond to the concept of cost effectiveness.

4.4 Results

Marginal abatement curves for emissions of HFCs, PFCs and SF_6 have been calculated for the four model regions for 2010 and 2020 (see Annex II Marginal abatement curves (regions). Below they are reported as aggregates on the global level in Figure 12 and Figure 13.

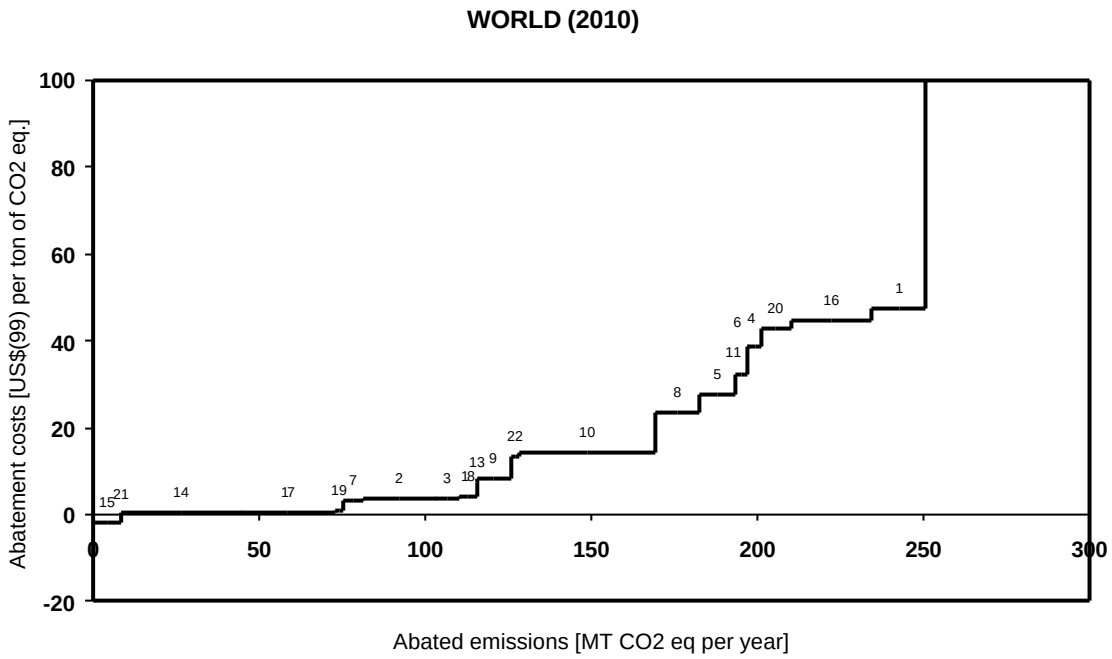

Figure 12 Global emission reduction supply curve[11] for HFCs, PFCs and SF_6 in 2010.

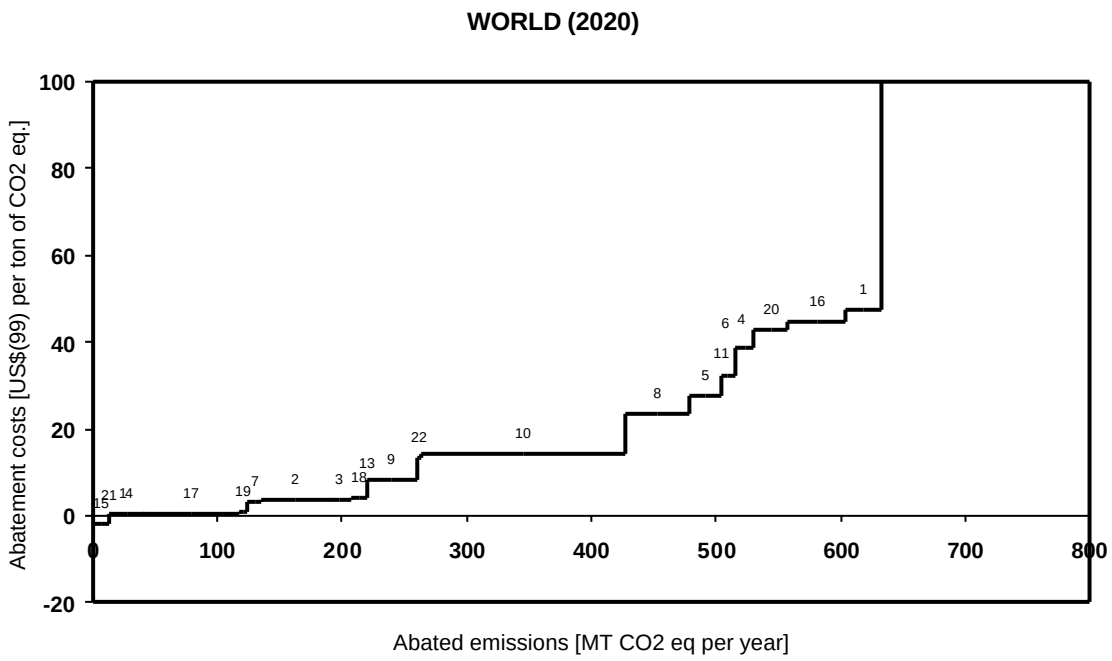

Figure 13 Global emission reduction supply curve[11] for HFCs, PFCs and SF_6 in 2020.

[11] The numbering of options refers to Table 6.

Table 7 gives an overview of the emission reduction potentials for different cost ranges in each of the regions. Above US$ per ton of CO_2 equivalent no estimates are given due to scarcity of data in the high cost range. Harnisch et al. (2000b) estimated that in the European Union 90% of projected emissions of HFCs, PFCs and SF_6 in 2010 are likely to be abatable at marginal costs below US$ 100 per ton of CO_2 equivalent. The situation in the other regions is likely to be similar though a different regulatory situation (e.g. on volatile organic compounds) in the USA and some other countries may lead to somewhat lower maximum penetration rates.

Table 7 Overview of emission reduction potentials for HFCs, PFCs and SF_6.

	2010	**Cost range[12]**			**2020**	**Cost range[12]**		
		<0	**0-20**	**20-50**		**<0**	**0-20**	**20-50**
Region	**Total emissions[13]**	**Reduction potential[13]**			**Total emissions[13]**	**Reduction potential[13]**		
North America	187	2	53	27	255	3	135	56
Western Europe	157	2	38	22	200	3	92	44
Japan	86	0	20	18	106	0	46	36
Rest of World	175	5	50	22	312	8	143	77
WORLD	605	9	161	89	873	14	416	213

On the global level this implies that in 2010 more than 40% of projected emissions can be abated at below US$ 50 per ton of CO_2 equivalent. This share increases to over 75% in 2020. The regional variance of these values is significantly smaller than calculated for energy intensive processes like for example the iron and steel industry [IEA GHG, 2000a and 2000b].

[12] Expressed as 1999 US$ per ton of CO_2 equivalent.
[13] Expressed as MT CO_2 equivalents per year

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Annex I Sectoral modelling of emissions

Commercial Refrigeration

Emissions are modelled by applying a time-dependent emission factor to the banked amounts of refrigerant per substance class. Respective refrigerant banks are calculated based on data in UNEP [1998a] which reports sums of fluorinated refrigerants used in the four main regions. A break-up into CFCs, HCFCs and HFC was calculated for this study by assuming the same split between substance classes as reported in UNEP [1998a] for all other refrigeration and stationary air conditioning applications. It is assumed that in the industrialised world CFC banks in this application will decrease by 10% per year of their 1996 value while this bank will remain unchanged in the rest of the world until 2020. For HCFCs it is assumed that banks decrease by 10% per year of their 1996 value in Western Europe and Japan, decrease by 5% per year in North America and geometrically grow by 5% per year in the Rest of World until 2010 and then stagnate. For Rest of the World it is assumed that the bank of refrigerant grows by 5% per year between 1996 and 2020 with HFCs filling any gap between projected bank size and projected banks of CFCs and HCFCs.

Table A1 Key parameters of emission model for commercial refrigeration

1. Commercial refrigeration	**CFC**	**HCFC**	**HFC-Bank**	**Emission-Factor[14]**
1996	**Bank [tons]**	**Bank [tons]**	**Bank [tons]**	
North America	16441	24416	4143	20% yr^{-1}
Western Europe	12788	18990	3222	20% yr^{-1}
Japan	7307	10852	1841	20% yr^{-1}
Rest of World	9134	13565	2301	20% yr^{-1}
TOTAL WORLD	45670	67823	11507	
2010				
North America	0	7325	37675	15% yr^{-1}
Western Europe	0	0	35000	15% yr^{-1}
Japan	0	0	20000	15% yr^{-1}
Rest of World	0	26857	22641	15% yr^{-1}
TOTAL WORLD	0	34182	115317	
2020				
North America	0	0	45000	10% yr^{-1}
Western Europe	0	0	35000	10% yr^{-1}
Japan	0	0	20000	10% yr^{-1}
Rest of World	0	26857	53771	10% yr^{-1}
TOTAL WORLD	0	26857	153771	

Cold storage and food processing

As described in the preceding paragraph, emissions are modelled by applying a time-dependent emission factor to the banked amounts of refrigerant per substance class.

[14] Including: Installation, leakage, servicing and maintenance and decommissioning.

Respective refrigerant banks are calculated based on data in UNEP [1998a] which reports values for CFCs, HCFCs and HFCs in this application. The break-up into the four main regions is carried out accordingly to the sums of banked refrigerant reported in UNEP [1998a] for commercial refrigeration. It is assumed that in the industrialised world CFC banks in this application will decrease by 10% per year of their 1996 value while this bank will remain unchanged in the rest of the world until 2020. For HCFCs it is assumed that banks decrease by 10% per year of their 1996 value in Western Europe and Japan, decrease by 5% per year in North America and geometrically grow by 5% per year in the Rest of World until 2010 and then stagnate. For Rest of the World it is assumed that the bank of refrigerant grows by 5% per year between 1996 and 2020 with HFCs filling any gap between projected bank size and projected banks of CFCs and HCFCs.

Table A2 Key parameters of emission model for cold storage and food processing

2. Cold storage and food processing	**CFC**	**HCFC**	**HFC-Bank**	**Emission-Factor[15]**
1996	**Bank [tons]**	**Bank [tons]**	**Bank [tons]**	
North America	30420	41940	2448	10% yr^{-1}
Western Europe	23660	32620	1904	10% yr^{-1}
Japan	13520	18640	1088	10% yr^{-1}
Rest of World	16900	23300	1360	10% yr^{-1}
TOTAL WORLD	84500	116500	6800	
2010				
North America	0	12582	62226	10% yr^{-1}
Western Europe	0	0	58184	10% yr^{-1}
Japan	0	0	33248	10% yr^{-1}
Rest of World	16900	46132	19254	10% yr^{-1}
TOTAL WORLD	16900	58714	172912	
2020				
North America	0	0	74808	10% yr^{-1}
Western Europe	0	0	58184	10% yr^{-1}
Japan	0	0	33248	10% yr^{-1}
Rest of World	16900	46132	71003	10% yr^{-1}
TOTAL WORLD	16900	46132	237243	

Industrial refrigeration

As described in the preceding paragraph, emissions are modelled by applying a time-dependent emission factor to the banked amounts of refrigerant per substance class. Respective refrigerant banks are calculated based on data in UNEP [1998a] which reports values for CFCs, HCFCs and HFCs in this application. The break-up into the four main regions is carried out accordingly to the sums of banked refrigerant reported in UNEP [1998a] for commercial refrigeration. It is assumed that in the industrialised world CFC banks in this application will decrease by 10% per year of their 1996 value while this bank will remain unchanged in the rest of the world until 2020. For HCFCs it is assumed that banks decrease by 10% per year of their 1996 value in Western Europe and Japan, decrease by 5% per year in North America and geometrically grow by 5% per year in the Rest of World until 2010 and then stagnate. For Rest of the World it is assumed that the bank of refrigerant grows by 5%

[15] Including: Installation, leakage, servicing and maintenance and decommissioning.

per year between 1996 and 2020 with HFCs filling any gap between projected bank size and projected banks of CFCs and HCFCs.

Table A3 Key parameters of emission model for industrial refrigeration

3. Industrial refrigeration	CFC	HCFC	HFC-Bank	Emission-Factor[16]
1996	**Bank [tons]**	**Bank [tons]**	**Bank [tons]**	
North America	10260	13860	792	10% yr^{-1}
Western Europe	7980	10780	616	10% yr^{-1}
Japan	4560	6160	352	10% yr^{-1}
Rest of World	5700	7700	440	10% yr^{-1}
TOTAL WORLD	28500	38500	2200	
2010				
North America	0	4158	20754	10% yr^{-1}
Western Europe	0	0	19376	10% yr^{-1}
Japan	0	0	11072	10% yr^{-1}
Rest of World	5700	15245	6457	10% yr^{-1}
TOTAL WORLD	5700	19403	57659	
2020				
North America	0	0	24912	10% yr^{-1}
Western Europe	0	0	19376	10% yr^{-1}
Japan	0	0	11072	10% yr^{-1}
Rest of World	5700	15245	23690	10% yr^{-1}
TOTAL WORLD	5700	15245	79050	

Air conditioning and reversible heat pumps

As described in the preceding paragraph, emissions are modelled by applying a time-dependent emission factor to the banked amounts of refrigerant per substance class. Respective refrigerant banks are calculated based on data in UNEP [1998a] which reports values for HCFCs and HFCs in this application (CFCs were not relevant to this sector). The break-up into the four main regions is carried out accordingly to the sums of banked refrigerant reported in UNEP [1998a] for commercial refrigeration. For HCFCs it is assumed that banks decrease by 5% per year of their 1996 value in Western Europe, Japan and North America and geometrically grow by 5% per year in the Rest of World until 2010 and then stagnate. For Rest of the World it is assumed that the bank of refrigerant grows by 5% per year between 1996 and 2020 with HFCs filling any gap between projected bank size and the projected bank of HCFCs.

[16] Including: Installation, leakage, servicing and maintenance and decommissioning.

Table A4 Key parameters of emission model for air conditioning and reversible heat pumps[17]

4. Air conditioning and reversible heat pumps	CFC	HCFC	HFC-Bank	Emission-Factor
1996	**Bank [tons]**	**Bank [tons]**	**Bank [tons]**	
North America	0	30520	0	10% yr^{-1}
Western Europe	0	23738	0	10% yr^{-1}
Japan	0	13564	0	10% yr^{-1}
Rest of World	0	16956	0	10% yr^{-1}
TOTAL WORLD	0	84778	0	
2010				
North America	0	9156	21364	10% yr^{-1}
Western Europe	0	7121	16616	10% yr^{-1}
Japan	0	4069	9495	10% yr^{-1}
Rest of World	0	33571	0	10% yr^{-1}
TOTAL WORLD	0	53918	47476	
2020				
North America	0	0	30520	10% yr^{-1}
Western Europe	0	0	23738	10% yr^{-1}
Japan	0	0	13564	10% yr^{-1}
Rest of World	0	33571	21113	10% yr^{-1}
TOTAL WORLD	0	33571	88935	

Transport refrigeration

As described in the preceding paragraph, emissions are modelled by applying a time-dependent emission factor to the banked amounts of refrigerant per substance class. Respective refrigerant banks are calculated based on data in UNEP [1998a] which reports values for CFCs, HCFCs and HFCs in this application. The break-up into the four main regions is carried out accordingly to the sums of banked refrigerant reported in UNEP [1998a] for commercial refrigeration. It is assumed that in the industrialised world CFC banks in this application will decrease by 10% per year of their 1996 value while this bank will remain unchanged in the rest of the world until 2020. For HCFCs it is assumed that banks decrease by 5% per year of their 1996 value in Western Europe, Japan and North America and geometrically grow by 5% per year in the Rest of World until 2010 and then stagnate. For Rest of the World it is assumed that the bank of refrigerant grows by 5% per year between 1996 and 2020 with HFCs filling any gap between projected bank size and projected banks of CFCs and HCFCs.

This sector comprises refrigerated containers, refrigerated railcars, road transport, air conditioned buses and rail cars, reefer ships, and the merchant marine & fishing vessels. According to UNEP [1998a] the maritime sources in 1996 were responsible for 75% of total emissions from transport refrigeration.

[17] Including: Production, installation, leakage, servicing and maintenance and decommissioning.

Table A5 Key parameters of emission model for transport refrigeration

5. Transport refrigeration	CFC	HCFC	HFC-Bank	Emission-Factor[18]
1996	**Bank [tons]**	**Bank [tons]**	**Bank [tons]**	
North America	3686	14666	2862	25% yr^{-1}
Western Europe	2867	11407	2226	25% yr^{-1}
Japan	1638	6518	1272	25% yr^{-1}
Rest of World	2048	8148	1590	25% yr^{-1}
TOTAL WORLD	10240	40740	7950	
2010				
North America	0	4400	16815	20% yr^{-1}
Western Europe	0	3422	13078	20% yr^{-1}
Japan	0	1956	7473	20% yr^{-1}
Rest of World	2048	16132	5155	20% yr^{-1}
TOTAL WORLD	2048	25910	42521	
2020				
North America	0	0	21215	15% yr^{-1}
Western Europe	0	0	16500	15% yr^{-1}
Japan	0	0	9429	15% yr^{-1}
Rest of World	2048	16132	19831	15% yr^{-1}
TOTAL WORLD	2048	16132	66975	

Heat pumps

As described in the preceding paragraph, emissions are modelled by applying a time-dependent emission factor to the banked amounts of refrigerant per substance class. Respective refrigerant banks are calculated based on data in UNEP [1998a] which reports values for CFCs, HCFCs and HFCs in this application. The break-up into the four main regions is carried out accordingly to the sums of banked refrigerant reported in UNEP [1998a] for commercial refrigeration. It is assumed that in the industrialised world CFC banks in this application will decrease by 10% per year of their 1996 value while this bank will remain unchanged in the rest of the world until 2020. For HCFCs it is assumed that banks decrease by 5% per year of their 1996 value in Western Europe, Japan and North America and geometrically grow by 5% per year in the Rest of World until 2010 and then stagnate. For Rest of the World it is assumed that the bank of refrigerant grows by 5% per year between 1996 and 2020 with HFCs filling any gap between projected bank size and projected banks of CFCs and HCFCs.

[18] Including: Production, installation, leakage, servicing and maintenance and decommissioning.

Table A6 Key parameters of emission model for heat pumps

6. Heat pumps	CFC	HCFC	HFC-Bank	Emission-Factor[19]
1996	**Bank [tons]**	**Bank [tons]**	**Bank [tons]**	
North America	1717	1603	420	10% yr^{-1}
Western Europe	1336	1247	326	10% yr^{-1}
Japan	763	712	187	10% yr^{-1}
Rest of World	954	890	233	10% yr^{-1}
TOTAL WORLD	4770	4452	1166	
2010				
North America	0	481	3259	10% yr^{-1}
Western Europe	0	374	2535	10% yr^{-1}
Japan	0	214	1448	10% yr^{-1}
Rest of World	954	1763	1397	10% yr^{-1}
TOTAL WORLD	954	2831	8638	
2020				
North America	0	0	3740	10% yr^{-1}
Western Europe	0	0	2909	10% yr^{-1}
Japan	0	0	1662	10% yr^{-1}
Rest of World	954	1763	3984	10% yr^{-1}
TOTAL WORLD	954	1763	12294	

Domestic refrigeration

As described in the preceding paragraph, emissions are modelled by applying a time-dependent emission factor to the banked amounts of refrigerant per substance class. Respective refrigerant banks are calculated based on data in UNEP [1998a] which reports consumption data for CFCs, HCFCs and HFCs in this application for the years 1992 and 1996 on a regional level. Banks of refrigerant for the year 1996 are calculated by adding eight times the 1992 consumption and four times 1996 consumption albeit reflecting a reasonable mix of working fluids for a mean lifetime of 12 years. It is assumed that in the industrialised world CFC banks in this application will decrease by 10% per year of their 1996 value while this bank will remain unchanged in the rest of the world until 2020. For HCFCs it is assumed that banks decrease by 5% per year of their 1996 value in Western Europe, Japan and North America and geometrically grow by 5% per year in the Rest of World until 2010 and then stagnate. For Rest of the World it is assumed that the bank of refrigerant grows by 5% per year between 1996 and 2020 with HFCs filling any gap between projected bank size and projected banks of CFCs and HCFCs.

[19] Including: Production / installation, leakage, servicing and maintenance and decommissioning.

Table A7 Key parameters of emission model for domestic refrigeration[20]

7. Domestic Refrigeration	CFC	HCFC	HFC-Bank	Emission-Factor
1996	**Bank [tons]**	**Bank [tons]**	**Bank [tons]**	
North America	35226	459	10962	5% yr^{-1}
Western Europe	27398	357	8526	5% yr^{-1}
Japan	15656	204	4872	5% yr^{-1}
Rest of World	19570	255	6090	5% yr^{-1}
TOTAL WORLD	97850	1275	30450	
2010				
North America	0	138	46509	5% yr^{-1}
Western Europe	0	107	36174	5% yr^{-1}
Japan	0	61	20671	5% yr^{-1}
Rest of World	19570	505	31235	5% yr^{-1}
TOTAL WORLD	19570	811	134589	
2020				
North America	0	0	46647	5% yr^{-1}
Western Europe	0	0	36281	5% yr^{-1}
Japan	0	0	20732	5% yr^{-1}
Rest of World	19570	505	63504	5% yr^{-1}
TOTAL WORLD	19570	505	167164	

Mobile air conditioning (MAC)

The emission model for this sector takes into account the sizes of vehicle fleets according to the Fischer (1999). The number of vehicles is assumed to remain constant in North America and Japan between 1996 and 2020. It is assumed to grow by 2% per year in Europe until 2010 and remain constant while growth rates of +5% and +3% are assumed for Rest of World for the time until 2010 and the subsequent decade, respectively. It is assumed that in all four regions specific mean refrigerant charges per vehicle decrease from 0.7 kg to 0.65 kg to 0.60 kg per vehicle in 1996, 2010 and 2020, respectively. The share of MAC in vehicle fleets is projected to increase from 80% to 85% in North America and Japan until 2010 and remain constant thereafter. For Western Europe an increase from 30% via 70% to 80% is anticipated from 1996 to 2010 to 2020. Rest of World is estimated to show a comparable increase from 20% via 50% to 75%. The share of HFC-134a in existing MAC in 1996 is estimated to have been 50% in Japan and North America, 70% in Western Europe and 30% in Rest of World.

[20] Including: Production, leakage, servicing and decommissioning.

Table A8 Key parameters of emission model for mobile air conditioning

8. Mobile air conditioning	CFC	HCFC	HFC-Bank	Emission-Factor[21]
1996	**Bank [tons]**	**Bank [tons]**	**Bank [tons]**	
North America	65600	0	65600	25% yr^{-1}
Western Europe	12953	0	30223	25% yr^{-1}
Japan	22176	0	22176	25% yr^{-1}
Rest of World	5309	0	12387	25% yr^{-1}
TOTAL WORLD	106038	0	130386	
2010				
North America	0	0	121975	10% yr^{-1}
Western Europe	0	0	116313	10% yr^{-1}
Japan	0	0	41234	10% yr^{-1}
Rest of World	0	0	76643	10% yr^{-1}
TOTAL WORLD	0	0	356165	
2020				
North America	0	0	113263	8% yr^{-1}
Western Europe	0	0	123435	8% yr^{-1}
Japan	0	0	38288	8% yr^{-1}
Rest of World	0	0	161473	8% yr^{-1}
TOTAL WORLD	0	0	436459	

Extruded polystyrene (XPS), polyurethane (PU) & polyisocyanurate (PIR)

Emissions from rigid foams are calculated according to the simple procedure introduced by Gamlen et al. (1986) which assumes a 10% loss of blowing agent during production a an annual loss 4.5% of blowing agent for next 20 years. This procedure does not take into account specific emission characteristics of classes of foam products. In the past it has nevertheless proven to be very successful to estimate global emissions. Consumption data for CFC-11, HCFC-141b, HCFC-142b and HCFC-22 for the regions in 1997 were taken from UNEP (1998b). Globally a 1:1 substitution of HCFC and CFCs by HFCs was assumed for the baseline scenario. It was also assumed that globally foam production (and blowing agent consumption) would grow by 3% per year between 1997 and 2020. It was also assumed that the regional distribution of foam production (XPS and PU/PIR) would remain unchanged in time relative to the 1997 situation.

[21] Production, leakage, servicing and maintenance and decommissioning.

Table A9 Key parameters of emission model for extruded polystyrene (XPS) and polyurethane (PU) and polyisocyanurate (PIR)

	Bank 1996 [tons]	Use 1997 [tons per year]	Bank 2010 [tons]	Use 2010 [tons per year]	Bank 2020 [tons]	Use 2010 [tons per year]
CFC-11	2072629	55000	766873	0	0	0
CFC-12	477170	0	176553	0	0	0
HCFC-22	52943	13000	84353	0	28939	0
HCFC-142b	208297	36000	275847	0	94634	0
HCFC-141b	208114	96000	497662	0	170731	0
HFC-134a	3836	3579	405706	60210	1133959	80917
HFC-245/365	0	0	1480282	234965	4322247	315774
TOTAL	3022989	203579	3687276	295175	5750509	396691

Solvents

Historically the usage of ozone depleting substances in this field has been high (in 1989: 136,000 tons of CFC-113 and 707,000 tons of trichloroethane [UNEP, 1999a]). Due to the generally highly emissive nature of solvent applications, large efforts have been directed to replace ozone depleting substances by other technical solutions. The resulting dynamics have led to a transitory situation that makes it difficult to characterise the current global solvent markets and even more difficult to develop meaningful scenarios for its future evolution. Here, respective estimates are made for the year 1996 on the basis of data reported in UNEP [1998e, 1999a] and Midgley and McCulloch [1999]. It is assumed that the global use of trichloroethane had declined to insignificance by 1996 [Midgley and McCulloch, 1999]. For the future it is assumed that the industrialised countries switch completely to HFCs by 2010. Regarding the market in Rest of World it is assumed that the switch away from CFCs into HCFCs will be accomplished by 2010 and then be followed by a full transition into HFCs until 2020. Due to the many alternative solutions and increasing solvent prices from CFCs into HCFCs into HFCs no growth of the markets is anticipated.

Table A10 Key parameters of emission model for solvent applications.

10. Solvents	CFC	HCFC	HFC-Bank	Emission-Factor
1996	**Usage [tons]**	**Usage [tons]**	**Usage [tons]**	
North America	0	8000	0	100% yr^{-1}
Western Europe	0	6400	0	100% yr^{-1}
Japan	0	5000	0	100% yr^{-1}
Rest of World	33000	0	0	100% yr^{-1}
TOTAL WORLD	33000	19400	0	
2010				
North America	0	0	8000	100% yr^{-1}
Western Europe	0	0	6400	100% yr^{-1}
Japan	0	0	5000	100% yr^{-1}
Rest of World	0	10000	0	100% yr^{-1}
TOTAL WORLD	0	10000	19400	
2020				
North America	0	0	8000	100% yr^{-1}
Western Europe	0	0	6400	100% yr^{-1}
Japan	0	0	5000	100% yr^{-1}
Rest of World	0	0	10000	100% yr^{-1}
TOTAL WORLD	0	0	29400	

Metered dose inhalers (MDI)

UNEP [1998d] estimates that the global consumption of CFCs for MDIs was 10,000 tons in 1996. Thereof industrialised countries used roughly 7,900 tons. The consumption across the three industrialised regions of the emission model were broken up according to population numbers after Fischer [1999]. For North America, Western Europe and Japan a growth rate of MDI use of +3% per year was assumed. A higher growth rate of +5% per year is assumed for Rest of World between 1996 and 2020. A 100% CFC usage is assumed for 1997 as opposed to 100% HFC in 2010 and 2020.

Technical aerosols

Campbell [1999] estimates that the global consumption of HFCs in 1999 did not exceed 15,000 tons per year in 1997. The consumption across the three industrialised regions of the emission model were broken up corresponding to population numbers according to Fischer [1999]. In the USA a production of technical aerosols using HCFCs still occurs but has not been included into the model due to a lack of respective data. UNEP [1998d] estimates that developing and transition countries consumed about 15,000 tons of CFCs in 1997.
For North America, Western Europe and Japan a growth rate of technical aerosol uses of +3% per year was assumed. A higher growth rate of +5% per year is assumed for Rest of World between 1996 and 2020. It is assumed that by 2010 all regions will have switched to 100% HFC use.

Production of HCFC-22

Emissions from this source are modelled as linked to production of hydrochlorfluorocarbon-22 through a time dependent emission factor. For Rest of World this factor is assumed to be a

constant 2% HFC-23 per mass unit of HCFC-22 produced. In North America, Western Europe and Japan this factor is assumed to decline from 2% in 1996 to 0.5% in 2010 and thereafter as the implementation of emission abatement equipment is mandated. Production data for 1995 were taken from Branscome and Irving (1999) for Western Europe, North America and Japan. Comparable data for the countries of Rest of World were obtained by assuming that all of HCFC production reported by these countries to UNEP [1999b] (in ODP-tons) was HCFC-22. In addition, it was also assumed that feedstock consumption of HCFC-22 (which would not be reported to UNEP) was insignificant for the ROW countries. For Western Europe, North America and Japan production of HCFC-22 is projected to remain constant until 2010 with increases in feedstock use and exports roughly compensating for declining consumption on internal markets. From 2010 to 2020 these regions are projected to exhibit a decline of HCFC-22 production due to a progressive global phase-out of HCFC. By then feedstock use of HCFC-22 will consume most of the HCFCs produced. For Rest of World an increase of production by +5% per year is projected for the time between 1996 and 2010. It is assumed that this production will remain constant thereafter.

Primary aluminium production

The emission data used for this study are taken from a recent study [IEA GHG, 2000a] in which estimates of emissions and a characterisation of respective abatement options were for a number of world regions. Regional data were aggregated appropriately into the four regions used for this study. To derive a baseline scenario for PFC emissions from this source it was assumed that 1995 emission levels will decrease to 80% of their 1995 value until 2010 and fall to 80% of that value by 2020. This implies that some decommissioning and retrofitting continues to take place and that new smelting capacity exhibits virtually no PFC emissions as compared to the existing mix of smelters.

Semiconductor production

The regional market shares of sub-micron technology in 1996 as reported by Bartos and Burton [1999] is projected to remain constant until 2020. Available 1996 emission data for the USA (US-EPA, 1999) were scaled accordingly to the other regions. The evolution of emissions along with expanding production is assumed to take place at a linear growth rate of 50% of documented mean US-growth of PFC emissions between 1990 to 1996 in each of the regions. This leads to a significantly reduced increase of baseline emissions against that calculated from an extrapolation of historic growth rates (+15% per year) of semiconductor production. The later approach would however not include technological improvements that are currently taking place in this industry (e.g. use of NF_3 for chamber clean in new equipment).

Magnesium production and casting

Market information on primary and secondary magnesium production were taken from Kramer [1995, 1996, 1997, 1998 and 1999]. It was assumed that in the reference case specific emissions per ton of metal processed (primary or secondary produced or die-casted) remain constant at a value of 2 Kg SF_6 per t of metal (Harnisch & Hendriks, 2000). For growth scenarios it was assumed that the primary production of magnesium grows at +2% per year across all regions. Secondary production is assumed to grow at a rate of +3% per year until 2010 and at +2% per year thereafter until 2020 in all four world regions. The current and future use of magnesium in die-casting is assumed to be linked to the use of light weight

magnesium parts in the automotive industry. The mass of all magnesium parts per vehicle is projected to grow from 2Kg in 1996 to 5Kg in 2010 to 20Kg in 2020. Car production is projected to remain at constant 1996 levels throughout 2020 in North America, Western Europe and Japan as opposed to Rest of World which is projected to exhibit a growth of vehicle output by +4% per year between 1996 and 2020. Data on car production on a per country basis were obtained from Fischer [1999].

Use of gas insulated switch gear (GIS)

Data on the size of banks of SF_6 in gas insulated switchgear in different world regions were taken from the industry survey CAPIEL / UNIPEDE (1998) (Table A11). Values of effective leakage rates across Europe in 1995 were taken from Neumann [1999]. Even within Europe leakage rates were found to vary between 0.5 and 5% per year. Based on an expert judgement, it is assumed for the emission model that leakage rates in the North America and Rest of World were at 5% in 1995 and will decrease to 2.5% per year until 2010 and remain constant thereafter. For Western Europe and Japan constant leakage rates of 2.5 % per year throughout the period 1995 to 2020 assumed. Regarding the future evolution of banked amounts of SF_6 it was assumed that these values will remain constant in North America, Western Europe and Japan reflecting the industry trend towards reduced charges per piece of equipment that compensates for some growth. In Rest of World the size of the bank of SF_6 is assumed to grow at 3% per year between 1995 and 2020.

Table A11 Amounts of SF_6 banked in GIS in 1995 after CAPIEL / UNIPEDE (1998)

Region	**Banked amount of SF6**
	[metric tons]
North America	3000
Europe	4500
South East Asia	6000
Japan	6200
Australia	1000
Near East	3500
South America	700
South Africa	700
TOTAL	25600

Manufacture of gas insulated switch gear (GIS)

The regional distribution of manufacturing of GIS in terms of SF_6 charges (Table A12) was estimated on the basis of market shares communicated by Bitsch & Wouda (private communication). For North America, Western Europe and Japan it was assumed that production capacity remains constant between 1995 and 2020 while a growth of 3% per year is anticipated for Rest of World. Specific emission rates of SF6 in manufacturing are assumed to remain at a its 1995 level of 12.5 % of charged SF6 in Western Europe and decrease from 25 % in 1995 to 12.5 % until 2010 and remain constant thereafter in the other three world regions.

Table A12 Distribution of GIS manufacture in 1995

REGION	Manufactured GIS as SF_6 [tons per year]
North America	63
Western Europe	1250
Japan	1406
Rest of World	313
TOTAL	3031

Fire fighting

Global estimates of halon emissions in 1996 were taken from Midgley and McCulloch [1999]. To assign them to the four model regions, sums of sales of halons between 1986 and 1997 were used for different countries as reported by UNEP [1999b] aggregated into ODP-tons for the different types of halons.

Halon emissions in the industrialised countries are assumed to decline to zero until 2010. In Rest of World halon emissions are assumed to go down to 80% and 50% of 1996 values in 2010 and 2020, respectively. For all four regions it is assumed that HFCs and PFCs fully compensate for declining use of halons by maintaining the 1996 level of banked fire-extinguishing fluids until 2010 and 2020. For Rest of World an additional growth of the fluid bank by +3% per year is allowed for. Overall emission rates are projected to remain constant at 1996 levels.

Fumigation with methyl bromide

Values for the consumption of methyl bromide in different regions were taken from the UNEP Handbook [UNEP, 1999b]. It is assumed that generally emissions of methyl bromide equal 50% of consumption to allow for effects due to absorption and destruction [Yates et al., 2000]. Following the regulations of the Montreal Protocol it is assumed that anthropogenic emissions of methyl bromide from North America, Western Europe and Japan decline to a value of virtually zero in 2010 and remain there until 2020. For Rest of World it is assumed that emissions decline by 20% of their 1997 levels until 2010 and then fall to virtually zero in 2020.

Manufacturing and distribution losses

Emissions of CCl_4 were dominating this sector in 1995. CCl_4 is mainly emitted during the manufacture of CFCs and related to certain processes. Data on the distribution of these emissions - which in 1996 were concentrated to Rest of World - were taken from UNEP [1998d]. It is assumed that emissions of CCl_4 will virtually disappear until 2010 as a consequence of the Montreal Protocol.

For HFCs, PFCs and SF_6 manufacturing and distribution losses are assumed to decrease from 2% of production in 1996, to 1.5% of production in 2010 down to 1% of production in 2020. Production of PFCs and SF_6 is projected to remain unchanged at 1995 levels as estimated by Harnisch et al. [1998] and Maiss and Brenninkmeijer [1998]. The production of HFCs is projected to grow from 74,000 tons per year to 390,000 tons yr^{-1} in 2010 to 450,000 tons yr^{-1} in 2010. Due to the minor relevance of this source emission are reported as HFC-134a.

Annex II Marginal abatement curves (regions)

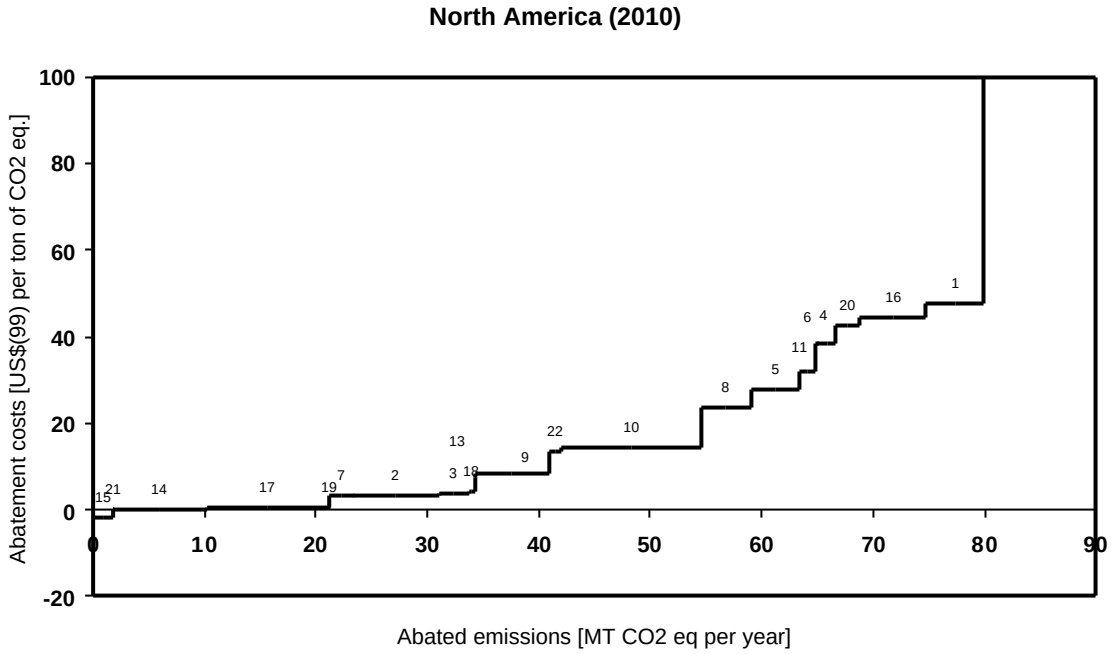

Figure A1 North American emission reduction supply curve[22] for HFCs, PFCs and SF_6 in 2010.

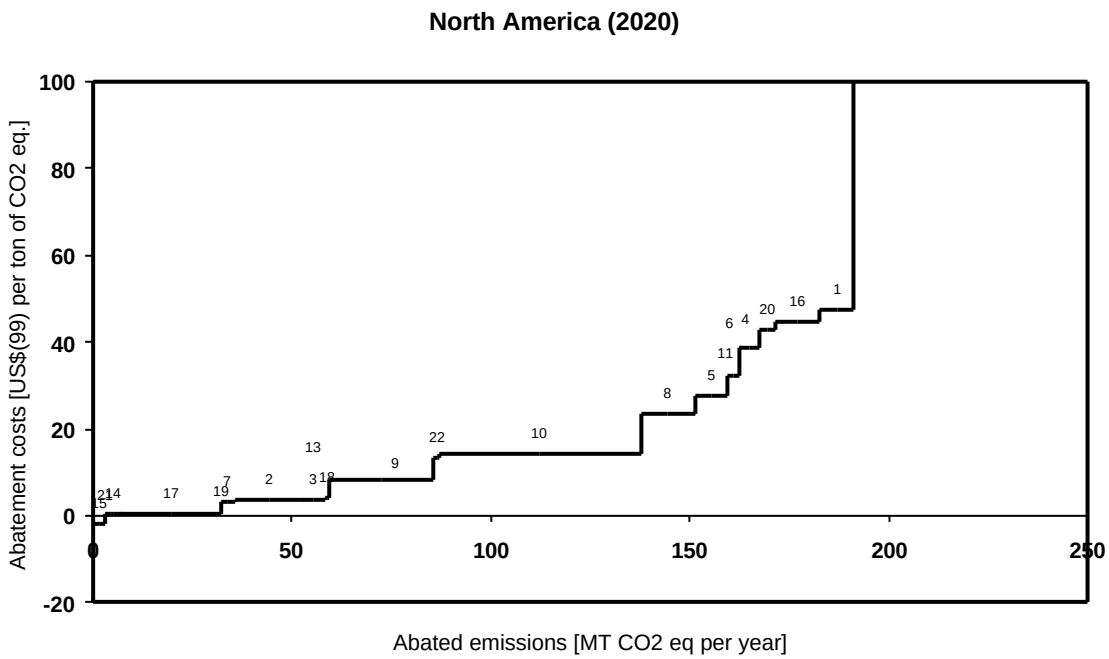

Figure A2 North American emission reduction supply curve[22] for HFCs, PFCs and SF_6 in 2020.

[22] The numbering of options refers to Table 6.

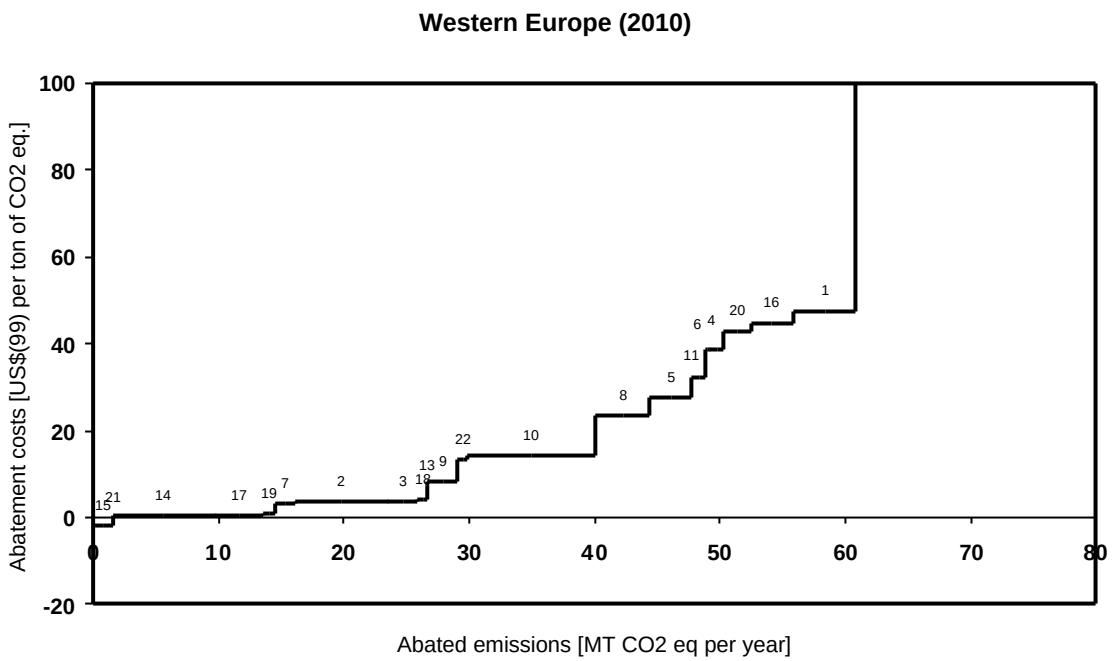

Figure A3 Western European emission reduction supply curve[23] for HFCs, PFCs and SF_6 in 2010.

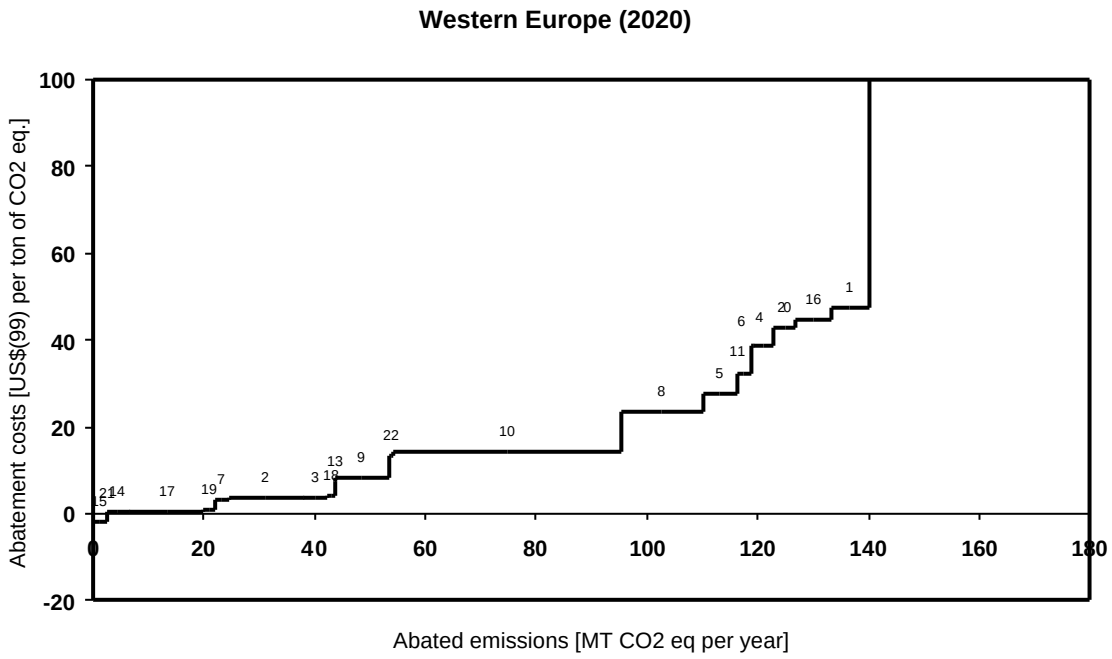

Figure A4 Western European emission reduction supply curve[23] for HFCs, PFCs and SF_6 in 2020.

[23] The numbering of options refers to Table 6.

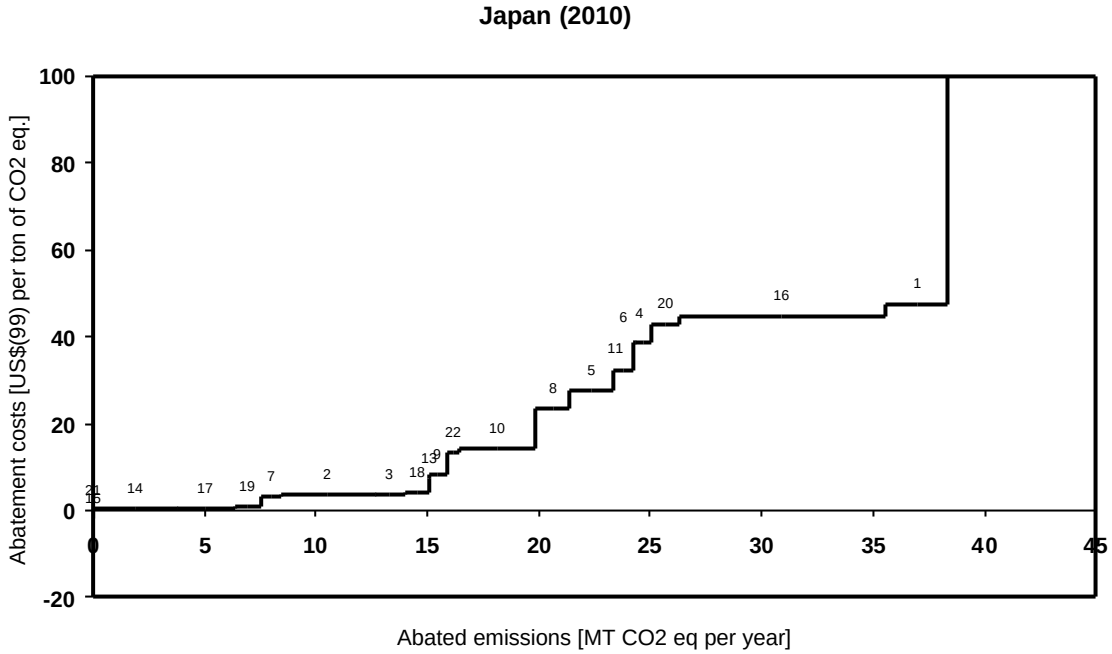

Figure A5 Japanese emission reduction supply curve[24] for HFCs, PFCs and SF_6 in 2010.

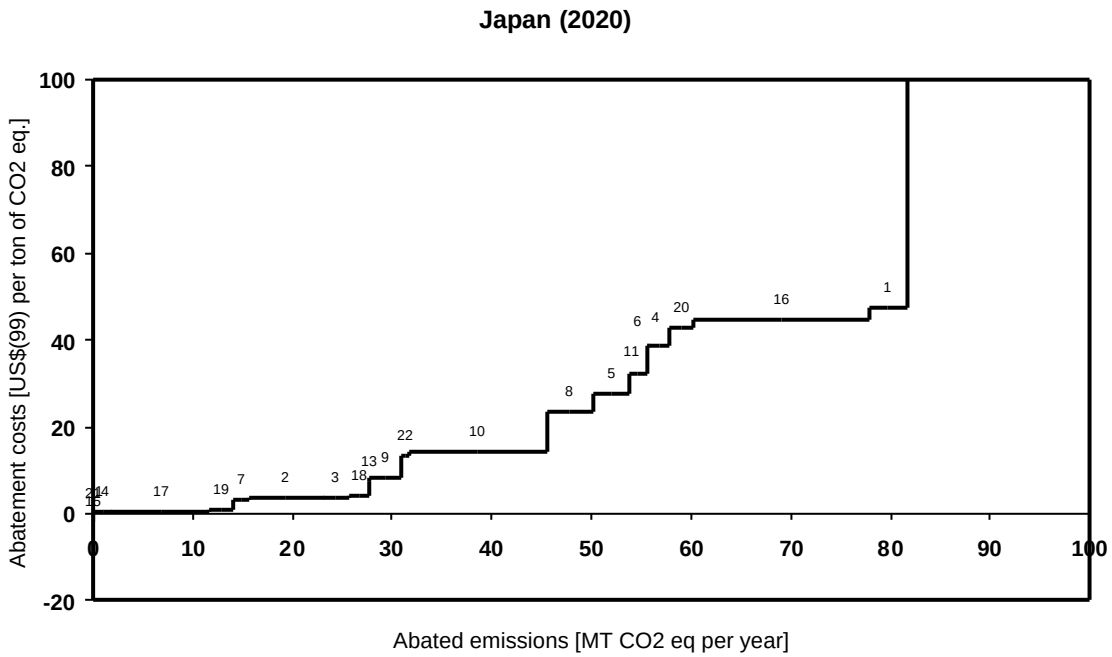

Figure A6 Japanese emission reduction supply curve[24] for HFCs, PFCs and SF_6 in 2020.

[24] The numbering of options refers to Table 6.

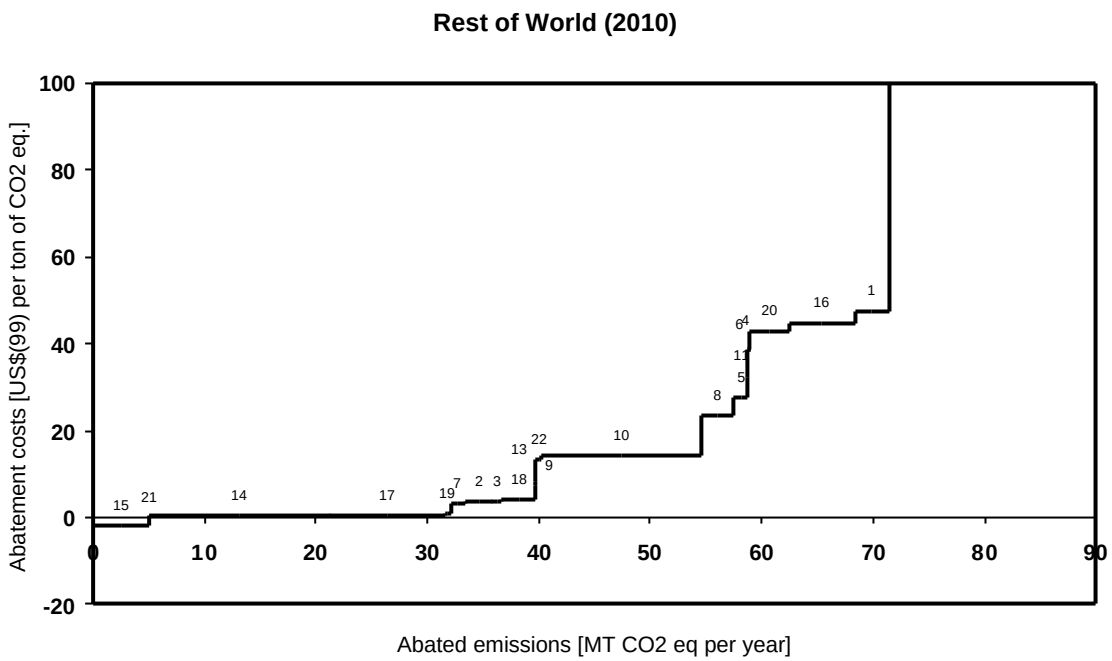

Figure A7 Rest of World emission reduction supply curve[25] for HFCs, PFCs and SF_6 in 2010.

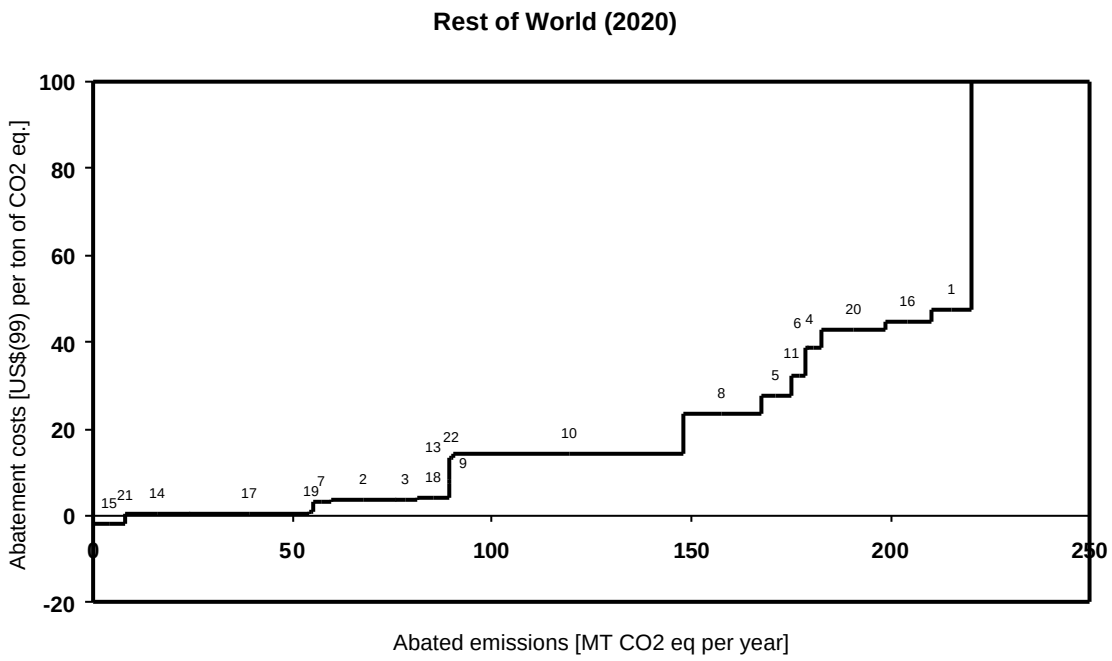

Figure A8 Rest of World emission reduction supply curve[25] for HFCs, PFCs and SF_6 in 2020.

[25] The numbering of options refers to Table 6.

ECOFYS

Annex III Calculations and data tables

Emission data per process and substance class
(metric tons of substance per year)

		HFCs				CFCs				HCFCs		
TranspRef		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**
North America		716	3363	3182		922	0	0		3667	880	0
Europe		557	2616	2475		717	0	0		2852	684	0
Japan		318	1495	1414		410	0	0		1630	391	0
ROW		398	1031	2975		512	410	307		2037	3226	2420
TOTAL		1988	8504	10046		2560	410	307		10185	5182	2420
		HFCs				CFCs				HCFCs		
Heat Pumps		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**
North America		42	326	374		172	0	0		160	48	0
Europe		33	253	291		134	0	0		125	37	0
Japan		19	145	166		76	0	0		71	21	0
ROW		23	140	398		95	95	95		89	176	176
TOTAL		117	864	1229		477	95	95		445	283	176
		HFCs				CFCs				HCFCs		
DomRef		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**
North America		438	2301	2308		1846	0	0		23	7	0
Europe		341	1790	1795		1436	0	0		18	5	0
Japan		195	1023	1026		821	0	0		10	3	0
ROW		244	1488	3084		1026	1026	1026		13	25	25
TOTAL		1218	6601	8213		5129	1026	1026		64	41	25
		HFCs				CFCs				HCFCs		
MobAirco		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**
North America		16400	12198	9061		16400	0	0		0	0	0
Europe		7556	11631	9875		3238	0	0		0	0	0
Japan		5544	4123	3063		5544	0	0		0	0	0
ROW		1327	7664	12918		3097	0	0		0	0	0
TOTAL		30827	35617	34917		28279	0	0		0	0	0

		HFC				CFC				HCFCs		
XPS		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**
North America		295	16319	39738		14473	5340	0		3219	9619	3300
Europe		108	5962	14517		5287	1951	0		1176	3514	1206
Japan		35	1947	4741		1727	637	0		384	1148	394
ROW		1	51	124		45	17	0		10	30	10
TOTAL		438	24278	59120		21533	7945	0		4790	14311	4910
		HFC				CFC				HCFC		
PU/PIR incl. OCF		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**
North America		0	27903	70007		29011	10686	0		4480	7522	2581
Europe		0	22744	57063		23647	8710	0		3652	6132	2104
Japan		0	7658	19213		7962	2933	0		1230	2064	708
ROW		0	31805	79796		33067	12180	0		5107	8574	2942
TOTAL		0	90109	226078		93687	34509	0		14469	24293	8334
		HFC				CFC				HCFC		
Solvents		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**
North America		0	8000	8000		0	0	0		8000	0	0
EU-15		0	6400	6400		0	0	0		6400	0	0
Japan		0	5000	5000		0	0	0		5000	0	0
ROW		0	0	10000		33000	0	0		0	10000	0
TOTAL		0	19400	29400		33000	0	0		19400	10000	0
		HFC				CFC				HCFC		
MDI		**1997**	**2010**	**2020**		**1997**	**2010**	**2020**		**1997**	**2010**	**2020**
North America		0	4307	5788		2933	0	0		0	0	0
Europe		0	5463	7342		3720	0	0		0	0	0
Japan		0	1821	2447		1240	0	0		0	0	0
ROW		0	3973	6472		2107	0	0		0	0	0
TOTAL		0	15564	22049		10000	0	0		0	0	0

		HFC				CFC				HCFC		
Tech Aerosols		**1997**	**2010**	**2020**		**1997**	**2010**	**2010**		**1997**	**2010**	**2020**
North America		0	8185	11000		0	0	0		5574	0	0
Europe		0	10382	13953		0	0	0		7070	0	0
Japan		0	3461	4651		0	0	0		2357	0	0
ROW		0	26399	43001		14000	0	0		0	0	0
TOTAL		0	48427	72605		14000	0	0		15000	0	0
HFC-23		**1995**	**2010**	**2020**								
North America		3100	775	388								
Europe		3000	750	375								
Japan		1390	348	174								
ROW		717	1490	1490								
TOTAL		8207	3363	2426								
		CF4					C2F6					
Aluminium		**1990**	**1995**	**2010**	**2020**		**1990**	**1995**	**2010**	**2020**		
North America		3192	1850	1480	1184		228	112	90	72		
Europe		3311	1511	1209	967		424	164	131	105		
Japan		0	0	0	0		0	0	0	0		
ROW		6031	5032	4025	3220		523	376	301	241		
Total		12534	8392	6714	5371		1175	652	522	417		
		Reported as CF4 equivalents										
Semiconductors		**1996**	**2010**	**2020**								
North America		789.5	1466.2	1949.6								
Europe		460.5	855.3	1137.3								
Japan		1250.1	2321.5	3086.9								
ROW		789.5	1466.2	1949.6								
Total		3290	6109	8123								

		SF6				SF6						
Mg-DieCast		**1996**	**2010**	**2020**		**Mg-Total**	**1996**	**2010**	**2020**			
North America		57	142	568		North Americ	463	705	1255			
Europe		53	132	526		Europe	139	245	665			
Japan		42	104	416		Japan	84	168	494			
ROW		33	143	846		ROW	433	674	1493			
Total		184	520	2356		Total	1119	1793	3907			
		SF6										
Mg-Primary		**1996**	**2010**	**2020**								
North America		266	351	428								
Europe		84	111	135								
Japan		0	0	0								
ROW		385	508	620								
Total		735	970	1183								
		SF6										
Mg-Secondary		**1996**	**2010**	**2020**								
North America		140	212	259								
Europe		2	3	4								
Japan		42	64	78								
ROW		15	23	28								
Total		200	303	369								
		SF6										
GIS-use		**1995**	**2010**	**2020**								
North America		150	75	75								
Europe		113	113	113								
Japan		155	155	155								
ROW		595	463	623								
Total		1013	806	965								

		SF6										
GIS-manuf		**1995**	**2010**	**2020**								
North America		16	8	8								
Europe		156	156	156								
Japan		352	176	176								
ROW		78	61	82								
Total		602	401	422								
		Halons				HFCs						
Halons		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**				
North America		2032	0	0		0	2032	2032				
Europe		2014	0	0		0	2014	2014				
Japan		1169	0	0		0	1169	1169				
ROW		4785	3828	1914		0	3410	7813				
Total		10000	3828	1914		0	8625	13028				
		MeBr										
MeBr		**1997**	**2010**	**2020**								
North America		10723	0	0								
Europe		9028	0	0								
Japan		2765	0	0								
ROW		9173	1835	0								
Total		31688	1835	0								
		HFCs				CFCs						
M&D losses		**1996**	**2010**	**2020**		**1996**	**2010**	**2020**				
North America		609	2132	1621		900	0	0				
Europe		522	1523	926		1800	0	0				
Japan		348	1218	926		900	0	0				
ROW		261	1218	1158		33200	0	0				
Total		1740	6090	4630		36800	0	0				

Global warming potentials used for different sectors

(based on Harnisch and Hendriks [2000] and IPCC [2000]: 100 year integration periods & average of maximum and minimum net-GWPs)

Name	CFC/Hal/MeBr	HCFC	HFC	PFC / SF6
COM REF	8600	1750	3145	
COLST + FPROC	8600	1750	2512	
IND REF	8600	1750	2512	
AirCo+HP	8600	1750	1882	
TranspRef	8600	1750	3196	
Heat Pumps	8600	1750	1882	
DomRef	8600	1750	1500	
MobAirco	8600	1750	1500	
XPS	8600	2100	830	
PU/PIR incl. OCF	1500	282.5	900	
Solvents	3700	282.5	900	
MDI	8600		2500	
Tech Aerosols	1500	282.5	830	
HFC-23			12000	
Alu				5700
Semis				5700
Magnesium				22200
GIS-use				22200
GIS-manuf				22200
Fire Fighting	-28225		3500	
MeBr	-1550			
M&D lossses	-1620		1500	

Tabulated values of aggregated emissions from different sectors

(All gases - using mean net-GWPs: MT CO_2 eq. per year)

		1996	**2010**	**2020**
1	COM REF	110	63	53
2	COLST + FPROC	95	68	82
3	IND REF	32	23	27
4	AirCo+HP	15	18	23
5	TranspRef	46	40	39
6	Heat Pumps	5	3	3
7	DomRef	46	19	21
8	MobAirco	289	53	52
9	XPS	196	119	59
10	PU/PIR incl. OCF	145	140	206
11	Solvents	128	20	26
12	MDI	86	39	55
13	Tech Aerosols	25	40	60
14	HFC-23	98	40	29
15	Alu	53	43	34
16	Semis	19	35	46
17	Magnesium	25	40	87
18	GIS-use	22	18	21
19	GIS-manuf	13	9	9
20	Fire Fighting	-282	-78	-8
21	MeBr	-49	-3	0
22	M&D lossses	-60	9	7
	TOTAL	1057	758	934

Annex IV - Phase-out schedules

Quoted after UNEP (2000)

Annex IV A – Group I: Chlorofluorocarbons (CFC-11, CFC-12, CFC-113, CFC-114 and CFC-115)

Applicable to production and consumption

Non-Article 5(1) Parties

Base level:	1986
Freeze:	July 1, 1989. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
75 percent: reduction	January 1, 1994. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
100 percent: reduction	January 1, 1996 (with possible essential use exemptions).
Allowance for production to meet the basic domestic needs of Article 5 Parties:	Annual average of its production for meeting the basic domestic needs of Article 5 parties for the period 1995 to 1997 inclusive till the end of 2002. January 1, 2003: 80 per cent of annual average of its production for basic domestic needs for the period 1995 to 1997 inclusive. January 1, 2005: 50 per cent of annual average of its production for basic domestic needs for the period 1995 to 1997 inclusive. January 1, 2007: 15 per cent of annual average of its production for basic domestic needs for the period 1995 to 1997 inclusive. January 1, 2010: zero.

Article 5(1) Parties

Base level:	Average of 1995–97
Freeze:	July 1, 1999. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
50 percent: reduction	January 1, 2005. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
85 percent: reduction	January 1, 2007. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
100 percent: reduction	January 1, 2010 (with possible essential use exemptions). Allowance for production to meet the basic domestic needs of Article 5 parties: 15 percent of base level production.

Annex IV A – Group II: Halons (halon 1211, halon 1301 and halon 2402)

Applicable to production and consumption

Non-Article 5(1) Parties

Base level:	1986
20 percent: reduction	January 1, 1992. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
100 percent: reduction	January 1, 1994 (with possible essential use exemptions).
Allowance for production to meet the basic domestic needs of Article 5 Parties	15 per cent of base level production until 1 January 2002; thereafter, the annual average of its production for meeting the basic domestic needs of Article 5 parties for the period 1995 to 1997 inclusive. January 1, 2005: 50 per cent of annual average of its production for basic domestic needs for the period 1995 to 1997 inclusive. January 1, 2010: zero.

Article 5(1) Parties

Base level:	Average of 1995–97
Freeze:	January 1, 2002. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
50 percent: reduction	January 1, 2005. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
100 percent: reduction	January 1, 2010 (with possible essential use exemptions). Allowance for production to meet the basic domestic needs of Article 5 parties: 15 percent of base level production.

Annex IV B – Group I: Other fully halogenated CFCs (CFC-13, CFC-111, CFC-112, CFC-211, CFC-212, CFC-213, CFC-214, CFC-215, CFC-216, CFC-217)

Applicable to production and consumption

Non-Article 5(1) Parties

Base level:	1989
20 percent: reduction	January 1, 1993. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
75 percent: reduction	January 1, 1994. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
100 percent: reduction	January 1, 1996 (with possible essential use exemptions).
Allowance for production to meet the basic domestic needs of Article 5 Parties:	15 per cent of base level production until 1 January 2003; thereafter, 80 percent of the annual average of its production for meeting the basic domestic needs of Article 5 parties for the period 1998 to 2000 inclusive. January 1, 2007: 15 per cent of annual average of its production for basic domestic needs for the period 1998 to 2000 inclusive. January 1, 2010: zero.

Article 5(1) Parties

Base level:	Average of 1998–2000
20 percent: reduction	January 1, 2003. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
85 percent: reduction	January 1, 2007. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
100 percent: reduction	January 1, 2010 (with possible essential use exemptions). Allowance for production to meet the basic domestic needs of Article 5 parties: 15 percent of base level production.

Annex IV B – Group II: Carbon tetrachloride

Applicable to production and consumption

Non-Article 5(1) Parties

Base level:	1989
85 percent reduction:	January 1, 1995. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
100 percent reduction:	January 1, 1996 (with possible essential use exemptions). Allowance for production to meet the basic domestic needs of Article 5 parties: 15 percent of base level production

Article 5(1) Parties

Base level:	Average of 1998–2000
85 percent: reduction	January 1, 2005. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
100 percent: reduction	January 1, 2010 (with possible essential use exemptions). Allowance for production to meet the basic domestic needs of Article 5 parties: 15 percent of base level production.

Annex IV B – Group III: 1,1,1-trichloroethane (methyl chloroform)

Applicable to production and consumption

Non-Article 5(1) Parties

Base level:	1989
Freeze:	January 1, 1993. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
50 percent: reduction	January 1, 1994. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
100 percent: reduction	January 1, 1996 (with possible essential use exemptions). Allowance for production to meet the basic domestic needs of Article 5 parties: 15 percent of base level production.

Article 5(1) Parties

Base level:	Average of 1998–2000
Freeze:	January 1, 2003. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
30 percent: reduction	January 1, 2005. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
70 percent: reduction	January 1, 2010. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production.
100 percent: reduction	January 1, 2015 (with possible essential use exemptions). Allowance for production to meet the basic domestic needs of Article 5 parties: 15 percent of base level production.

Annex IV C – Group I: HCFCs

Applicable to production and consumption

Non-Article 5(1) Parties: Consumption

Base level:	1989 HCFC consumption + 2.8 percent of 1989 CFC consumption.
Freeze:	1996.
35 percent: reduction	January 1, 2004.
65 percent: reduction	January 1, 2010.
90 percent: reduction	January 1, 2015.
99.5 percent: reduction	January 1, 2020, and thereafter, consumption restricted to the servicing of refrigeration and air-conditioning equipment existing at that date.
100 percent: reduction	January 1, 2030.

Non-Article 5(1) Parties: Production

Base level:	1989 HCFC production + 2.8 percent of 1989 CFC production.
Freeze:	January 1, 2004, at the level of the average of its base levels of production and consumption. Allowance for production to meet the basic domestic needs of Article 5 parties: 15 percent of base level production.

Article 5(1) Parties: Consumption

Base level:	2015.
Freeze:	January 1, 2016.
100 percent: Reduction	January 1, 2040.

Article 5(1) Parties: Production

Base level:	2015.
Freeze:	January 1, 2016, at the level of the average of its base levels of production and consumption. Allowance for production to meet the basic domestic needs of Article 5 parties: 15 percent of base level production.

Annex IV C – Group II: HBFCs

Applicable to production and consumption

Non-Article 5(1) Parties

100 percent: reduction	January 1, 1996 (with possible essential use exemptions).

Article 5(1) Parties

100 percent: reduction	January 1, 1996 (with possible essential use exemptions).

Annex IV C – Group III: Bromochloromethane

Applicable to production and consumption

Non-Article 5(1) Parties

100 percent: reduction	January 1, 2002 (with possible essential use exemptions).

Article 5(1) Parties

100 percent: reduction	January 1, 2002 (with possible essential use exemptions).

Annex IV E: Methyl bromide

Applicable to production and consumption, amounts used for quarantine and preshipment applications exempted.

Non-Article 5(1) Parties

Base level:	1991
Freeze:	January 1, 1995. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production to meet the basic domestic needs of Article 5 parties.
25 percent: reduction	January 1, 1999. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production to meet the basic domestic needs of Article 5 parties.
50 percent: reduction	January 1, 2001. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production to meet the basic domestic needs of Article 5 parties.
70 percent: reduction	January 1, 2003. Allowance for production to meet the basic domestic needs of Article 5 parties: 10 percent of base level production to meet the basic domestic needs of Article 5 parties.
100 percent: reduction	January 1, 2005 (with possible critical use exemptions).
Allowance for production to meet the basic domestic needs of Article 5 Parties:	15 per cent of base level production until 1 January 2002; thereafter, the annual average of its production for meeting the basic domestic needs of Article 5 parties for the period 1995 to 1998 inclusive. January 1, 2005: 80 per cent of annual average of its production for basic domestic needs for the period 1995 to 1998 inclusive. January 1, 2015: zero.

Article 5(1) Parties

Base level:	Average of 1995–98
Freeze:	January 1, 2002.
20 percent: reduction	January 1, 2005.
100 percent: reduction	January 1, 2015 (with possible critical use exemptions).

Annex V - Fluid properties

(modified after March (1998))

Fluid Name/Number	Chemical Formula	Usage Categories See Note 1	Flammability Category See Note 2	Toxicity Category See Note 3	ODP
Pure CFCs					
CFC 11	$CC1_3F$	U1, U2, U3, U4	F1	T1	1.0
CFC 12	$CC1_2F_2$	U1, U2, U4	F1	T1	1.0
CFC 13	$CC1F_3$	U1	F1	T1	1.0
CFC 113	$CC1_2FCC1F_2$	U1,U3	F1	T1	0.8
CFC 114	$CC1F_2CC1F_2$	U1	F1	T1	1.0
CFC 115	CF_3CC1F_2	U1	F1	T1	0.6
Pure HCFCs					
HCFC 22	$CHC1F_2$	U1, U2, U3	F1	T1	0.055
HCFC 123	$CHC1_2CF_3$	U1	F1	T2	0.020
HCFC 124	$CHC1FCF_3$	U1	F1	T1	0.022
HCFC 141b	$CC1_2FCH_3$	U2	F2	T1	0.110
HCFC 142b	$CC1F_2CH_3$	U1, U2	F2	T1	0.065
Pure HFCs					
HFC 23	CHF_3	U1	F1	T1	0.0
HFC 32	CH_2F_2	U1	F2	T1	0.0
HFC 125	CF_3CHF_2	U1	F1	T1	0.0
HFC 134a	CF_3CH_2F	U1, U2, U4	F1	T1	0.0
HFC 143a	CF_3CH_3	U1	F2	T1	0.0
HFC 152a	CHF_2CH_3	U1,U2	F1	T1	0.0
HFC 227ae	CF_3CHFCF_3	U4	F1	T1	0.0
HFC 245fa		U2	F1	T1	0.0
HFC 365mfc		U2	F1	T1	0.0

Usage Categories:
- U1 Refrigeration
- U2 Foam Blowing
- U3 Solvent
- U4 Aerosol Propellant
- U5 Other

Flammability Categories:
- F1 Non-flammable
- F2 Slightly flammable
- F3 Highly flammable

Toxicity Categories:
- T1 Very low toxicity
- T2 Slightly toxic
- T3 Highly toxic

Fluid Name/Number	Chemical Formula	Usage Categories See Note 1	Flammability Category See Note 2	Toxicity Category See Note 3	ODP
Pure PFCs					
PFC 14	CF_4	U5	F1	T1	0.0
PFC 116	C_2F_6	U5	F1	T1	0.0
PFC 218	C_3F_8	U1, U5	F1	T1	0.0
PFC 318	C_4F_{10}	U5	F1	T1	0.0
Pure HCs					
HC 50 (methane)	CH_4	-	F3	T1	0.0
HC 170 (ethane)	CH_3CH_3	-	F3	T1	0.0
HC 290 (propane)	$CH_3CH_2CH_3$	U1	F3	T1	0.0
HC 600 (butane)	C_4H_{10}	U1	F3	T1	0.0
HC 600a (iso-butane)	$CH(CH_3)_3$	U1	F3	T1	0.0
Pentane	C_5H_{12}	U2	F3	T1	0.0
Cyclopentane	C_5H_{12}	U2	F3	T1	0.0
HC 1150 (Ethylene)	$CH_2=CH_2$	U1	F3	T1	0.0
HC 1270 (Propylene)	C_3H_6	U1	F3	T1	0.0
Other Pure Fluids					
R717 Ammonia	NH_3	U1	F2	T3	0.0
R718 Water	H_2O	U1, U3	F1	T1	0.0
R744 CO_2	CO_2	U1, U2, U3, U4	F1	T1	0.0
R764 SO_2	SO_2	U1	F2	T3	0.0
Halon 1211	$CBrClF_2$	U5	F1	T1	3.0
Halon 1301 (R13B1)	$CBrF_3$	U1, U5	F1	T1	10.0
SF_6	SF_6	U5	F1	T1	0.0
NF_3	NF_3	U5	F1	T1	0.0

Usage Categories:
- U1 Refrigeration
- U2 Foam Blowing
- U3 Solvent
- U4 Aerosol Propellant
- U5 Other

Flammability Categories:
- F1 Non-flammable
- F2 Slightly flammable
- F3 Highly flammable

Toxicity Categories:
- T1 Very low toxicity
- T2 Slightly toxic
- T3 Highly toxic

Fluid Name/Number	Constituents of Blend	% Proportions	Usage Categories See Note 1	Flammability Category See Note 2	Toxicity Category See Note 3	ODP
CFC Azeotropes						
500	12/152a	73.8-26.2	U1	F1	T1	0.7
501	12/22	25-75	U1	F1	T1	0.26
502	115/22	51.2-48.8	U1	F1	T1	0.28
503	13/23	59.9-40.1	U1	F1	T1	0.6
HCFC Blends						
401A	22/152a/124	53-13-34	U1	F1	T1	0.04
401B	22/152a/124	61-11-28	U1	F1	T1	0.04
401C	22/152a/124	33-15-52	U1	F1	T1	0.03
402A	22/125/290	38-60-02	U1	F1	T1	0.02
402B	22/125/290	60-38-02	U1	F1	T1	0.03
403A	22/218/290	75-20-05	U1	F1	T1	0.04
403B	22/218/290	56-39-05	U1	F1	T1	0.03
406A	22/142b/600a	55-41-4	U1	F1	T1	0.06
408A	22/143a/125	47-46-07	U1	F1	T1	0.02
409A	22/124/142b	60-25-15	U1	F1	T1	0.05
409B	22/124/142b	65-25-10	U1	F1	T1	0.05
411B	22/152a/1270		U1	F1	T1	0.05
HFC Azeotropes						
507	125/143a	50-50	U1	F1	T1	0
508	23/116		U1	F1	T1	0

Usage Categories:
- U1 Refrigeration
- U2 Foam Blowing
- U3 Solvent
- U4 Aerosol Propellant
- U5 Other

Flammability Categories:
- F1 Non-flammable
- F2 Slightly flammable
- F3 Highly flammable

Toxicity Categories:
- T1 Very low toxicity
- T2 Slightly toxic
- T3 Highly toxic

Fluid Name/Number	Constituents of Blend	% Proportions	Usage Categories See Note 1	Flammability Category See Note 2	Toxicity Category See Note 3	ODP
HFC Blends						
404A	125/143a/134a	44/52/4	U1	F1	T1	0
407A	32/125/134a	20/40/40	U1	F1	T1	0
407B	32/125/134a	10-70-20	U1	F1	T1	0
407C	32/125/134a	23-25-52	U1	F1	T1	0
410A	32/125	50-50	U1	F1	T1	0
410B	32/125	45-55	U1	F1	T1	0
413A	134a/218/600a		U1	F1	T1	0
Isceon 59			U1	F1	T1	0
Isceon 89	125/218/290		U1	F1	T1	0
HC Blends						
Care 30	290/600a		U1	F3	T1	0
Care 50	170/290		U1	F3	T1	0

Usage Categories:
- U1 Refrigeration
- U2 Foam Blowing
- U3 Solvent
- U4 Aerosol Propellant
- U5 Other

Flammability Categories:
- F1 Non-flammable
- F2 Slightly flammable
- F3 Highly flammable

Toxicity Categories:
- T1 Very low toxicity
- T2 Slightly toxic
- T3 Highly toxic

Annex VI - Overview of options in key sectors

(modified after Harnisch et al. (2000c))

Table VI A The advantages and potential disadvantages of major emission reduction options available to the refrigeration and air conditioning sector.

	Option	Advantages	Disadvantages
1	use of non-HFC refrigerants (hydrocarbons or ammonia)	➢ no HFC emission ➢ no validation issues ➢ broad availability of proven technologies in most applications	➢ often higher investment costs for secondary systems ➢ flammability issues for primary systems ➢ often increased energy consumption for secondary systems ➢ potentially higher maintenance costs
2	use of alternative technology (e.g. absorption)	➢ no HFC emissions ➢ no validation issues	➢ often higher energy consumption
3	reduction of leakage rates through improved design and quality of components	➢ potentially very cost effective	➢ enforcement critical ➢ validation critical
4	reduction of leakage rates through improved maintenance	➢ potentially very cost effective	➢ enforcement critical ➢ validation critical
5	recovery during service and on disposal	➢ very cost effective for larger systems	➢ enforcement critical ➢ validation critical
6	minimising charge of required HFC refrigerant	➢ no flammability issues ➢ no significant increase of costs for primary systems	➢ increased energy consumption for secondary systems ➢ higher investment costs for secondary systems ➢ increasing servicing requirement
7	reduced demand for refrigeration and air conditioning	➢ energy savings	➢ often requires integrated solutions in e.g. architecture, logistics or agricultural policy

Table VI B The potential advantages and disadvantages of major emission reduction options available to the foam sector.

	Option	Advantages	Disadvantages
1	Alternative Blowing agent	➢ no HFC emissions ➢ lower material costs	➢ potential Insulation loss ➢ flammability (process) ➢ flammability (product) ➢ investment costs (SME) ➢ possible VOC emissions ➢ greater use of associated materials
2	Not-in-kind insulation (conventional)	➢ no HFC emissions	➢ potential insulation loss ➢ decrease in structural strength leading to increased weight and use of support materials ➢ lower moisture resistance ➢ fibre concerns
3	Not-in-kind insulation (vacuum insulation)	➢ no HFC emissions ➢ improved insulation performance	➢ higher production costs ➢ reduced flexibility in production and processing
4	Minimising HFC blowing agent	➢ reduced blowing agent costs	➢ limited ➢ potential insulation loss ➢ flammability ➢ density increase ➢ greater use of associated materials
5	Reduction of emission on manufacture through changes in processing practice		➢ unproven technical and economic feasibility ➢ investment costs
6	Reduction of emission in use through facing changes	➢ better retention of insulation value	➢ increased cost ➢ questionable market acceptance and feasibility for certain applications
7	Reduction of emission on de-commissioning through use of municipal incineration		➢ limited emission reduction potential ➢ separation costs ➢ needs development of separation technology and practice ➢ requires investment in incineration and infrastructure ➢ incineration by-product concerns ➢ requires regulation ➢ requires long term consistency of policy

Table VI C The potential advantages and disadvantages of major emission reduction options available for other sources of HFCs (Solvents, General Aerosol, MDI, Fire Fighting, Manufacturing and Distribution Losses)

	Option	Advantages	Disadvantages
1	**Drug Inhalors**		
	- DPI	➢ no HFC ➢ no monitoring required	➢ not suitable to all MDI patients (old, weak and very young persons) ➢ higher costs
2	**Solvents (HFCs)**		
	- Switching to HFE or other low GWP fluids	➢ often "drop in" solution	➢ limited emission reduction potential
	- Use of organic solvents	➢ lower fluid costs	➢ flammability
	- No clean technologies	➢ often reduction in energy consumption	➢ requires process modifications
	- Aqueous cleaning		➢ requires process modifications ➢ often reduced throughput ➢ sometimes higher energy consumption (drying)
3	**General Aerosols (HFCs)**		
	- Use of hydrocarbons	➢ lower costs ➢ no HFC-emissions	➢ flammability
	- Use of HFC / hydrocarbon / ether blends		➢ lower costs but not as low as for hydrocarbons ➢ flammability but less than for hydrocarbons
	- Other dispersion technologies	➢ no HFC emissions	➢ limited consumer acceptance ➢ often higher costs
4	**Fire-fighting**		
	- Alternative fluids	➢ no validation issues	➢ not always applicable
	- Leakage reduction	➢ Increased system reliability	➢ validation issues ➢ enforcement issues

Table VI D The potential advantages and disadvantages of major emission reduction options available for sources of PFC & SF_6 (Aluminium, Semiconductor Production

	Option	Advantages	Disadvantages
1	**Aluminium Production**		
	- Conversion to new technology	➢ often reduced energy and labour costs	➢ high investment costs
	- Retrofitting of existing smelter	➢ rather low investment costs ➢ often reduced energy and labour costs	➢ limited emission reduction potential
	- Increased recycling	➢ globally leads to reduced energy consumption	➢ leads only indirectly to PFC emission reductions if old smelters are closed
	- Inert Anodes	➢ reduces emissions of other air pollutants	➢ not a proven technology
2	**Semiconductor Production**		
	- Thermal oxidation	➢ generally high abatement efficiency	➢ increased energy consumption ➢ difficult to add to existing equipment ➢ high costs for fluoride disposal
	- Etching processes: Switching to other gases (from C_2F_6 to C_4F_8 / C_5F_{10})	➢ generally available at low costs	➢ only limited potential
	- CVD-chambers: Switching to NF_3 in	➢ large potential for new equipment ➢ increased throughput	➢ not suitable for retrofitting ➢ fluorine abatement required ➢ high costs for fluoride disposal
	- Improving PFC usage efficiency	➢ process integrated	➢ only limited potential
	- Capture and recovery of gases	➢ often lower investments on site	➢ high operating costs ➢ difficult to add to existing equipment
3	**HFC-23 emissions**		
	- process optimisation	➢ available at very low costs ➢ no investment costs	➢ significant emissions remain unabated
	- thermal oxidation of exhausts	➢ available at low costs	

Table VI E The potential advantages and disadvantages of major emission reduction options available for sources of SF_6 from Gas Insulated Switchgear, Magnesium Casting and others.

	Option	Advantages	Disadvantages
1	**Production of Gas Insulated Switchgear**		
	-improved recovery	➢ reduced gas costs	➢ sometimes investment in better pumps required ➢ potentially slowing down production
			➢ validation and enforcement issues
2	**Use of Gas Insulated Switchgear**		
	- reduced leakage rates	➢ potentially very low costs	➢ validation and enforcement issues
	- improved recovery for maintenance	➢ potentially very low costs	➢ validation and enforcement issues
	- improved recovery for end of life	➢ potentially very low costs	➢ validation and enforcement issues
	- air insulated switchgear (in new equipment)	➢ no validation issues	➢ larger equipment ➢ higher energy consumption if grid design is affected
	- exchange of existing switchgear against air insulated switchgear		➢ high costs ➢ often site relocations required
3	**Production of Magnesium**		
	- reducing specific usage rate	➢ small investment required	➢ validation issues
	- switching to SO_2	➢ lower gas costs ➢ no validation issues	➢ toxicity
4	**Other sources of SF_6**		
	Sound proof windows - alternative filling gases	➢ better thermal insulation performance	➢ somewhat less sound insulation value
	SF_6 filled tires - conventional air filling	➢ no emissions	