# Economic Evaluation of Emission Reductions of HFCs, PFCs and $SF_6$ in Europe

**SPECIAL REPORT**

**Contribution to the study**
“Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”
**on behalf of**
**the Commission of the European Union**
**Directorate General Environment**

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**Final Report**
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# Preface

On its way to its current form this report has received significant input from a considerable number of experts. The “First Interim Report” which basically dealt with emission estimates and projections has been significantly amended to also cover abatement options and associated costs. Comments on the “First Interim Report” were given by representatives of the European Commission at a presentation in Brussels on May 20, 1999. With approval of DG Environment the “Second Interim Report” has been distributed for comments to about 35 technical experts in late September 1999. It has also been circulated among the lead authors of Chapter 3 of Working Group 3 of the Third Assessment Report of the Intergovernmental Panel on Climate Change. A “Third Interim Report” was discussed by a panel of experts in Brussels on November 22, 1999. Specific and more general comments and suggestions were received from a large number of experts from industry, academia, government agencies and environmental non-governmental organisations. The authors would like to thank all of these experts for their valuable inputs into this study (please refer to chapter 10 for a list of people). For this “Final Report” it was attempted to consider their suggestions wherever possible. In several cases unresolved issues were flagged in footnotes. This final report reflects the state of knowledge and discussions after a final round of review in late March 2000.

Cologne - March 31st, 2000

# Contents

# 1 Introduction

The Kyoto Protocol under the United Nations Framework Convention on Climate Change (UNFCCC) regulates emissions of carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFC) are chemically related anthropogenic greenhouse gases. Because of their depleting effect on stratospheric ozone CFCs and HCFCs have been regulated under the Montreal Protocol since the late 1980's and were thus not included into the Kyoto Protocol. The whole group of fluorinated greenhouse gases (CFCs, HCFCs, HFCs, PFCs and $SF_6$) contributed about 25% of the added anthropogenic radiative forcing of the climate between 1980 and 1990 [IPCC, 1990]. The main contribution came from CFCs and HCFCs. It should be kept in mind that part of their direct warming effect is compensated by the indirect cooling effect due to their depleting effect on stratospheric ozone. The absolute relevance of the remaining fluorinated compounds (HFCs, PFCs, and $SF_6$) was limited to less than 1% of the added direct anthropogenic radiative effect during the same period. When the Kyoto Protocol was negotiated it was anticipated that emissions of HFCs, PFCs and $SF_6$ could contribute to global warming on a level comparable to CFCs and HCFCs. This notion was corroborated by rapidly increasing accumulation rates observed in the atmosphere. The extraordinary atmospheric stability of PFCs, $SF_6$ and some HFCs was an additional reason to restrict their emission [Cook, 1995]. Despite their limited present and near future relevance to global warming, is has been shown that the abatement of emissions of HFCs, PFCs and $SF_6$ can significantly reduce the total costs of compliance with the Kyoto Protocol [Reilly et al., 1999]. The same authors also demonstrated that a failure to control these emissions could be expensive if emissions increases have to be compensated by additional emission reductions from fossil fuels.

The main aim of this work is to provide a focussed analysis of the main sources and respective abatement options of emissions of HFCs, PFCs and $SF_6$ within the countries of the European Union. The study is complementary to the national activities to estimate emissions on a national level as for the second and upcoming third national communication under the United Nations Framework Convention on Climate Change. The report is not intended to be a check of such national data. The study consciously ignores the available national emission data in order to apply a simple and uniform methodology. The study aims to provide reasonable estimates of base year emissions in 1990 and 1995 on a country-by-country level, to derive a well-defined business as usual scenario for future emissions until 2010 and to identify and economically evaluate relevant abatement measures. It is the guiding principle of this study to clearly point out assumptions, to document how calculations were carried out and openly discuss uncertainties of results. We are not trying to duplicate the efforts of other comprehensive reports that give an overview over the multitude of minor and major sources [e.g. Novem/Ecofys, 1997; Pedersen, 1998; March, 1998; Ecofys, 1999]. Instead it is intended to provide a concise review of the main sources and key abatement options of the fluorinated greenhouse gases. The results of this study will be an input into the main study "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change" in which least cost solutions to reduce European greenhouse gas emissions will be numerically identified across economic sectors.

Emission estimates and projections in this study are made by using an abstracted bottom-up approach. While still close enough to the physical reality of emitting processes, this method remains simple enough not to obscure its results behind an excess of technical data and assumptions. As more knowledge about emissions of HFCs, PFCs and $SF_6$ accumulates it will become possible to step back and carry out true bottom-up analyses for each of the EU countries. The efforts currently undertaken for the third national communications of the parties of the Kyoto Protocol will certainly substantially increase the available knowledge on sources of emissions of these gases. The monitoring mechanism of Community $CO_2$ and other greenhouse gas emissions (Council Decision 1999/296/EC) is likely to significantly increase the impetus towards precise and transparent reporting and projection of emissions.

# 2 Methodology

## 2.1 Definition of sub-sectors

The definition of technological sub-sectors exhibits an arbitrary component. If a very wide sub-sector is defined it suggests that one policy instrument will suffice to cover it at one uniform abatement cost. This could either encourage hastened policies or prevent the realisation of inexpensive measures if they are hidden among significantly higher mean abatement costs. Very detailed definitions of sub-sectors on the other hand give good cost information and allow a very detailed design of appropriate policy tools. It may be the drawback of very fragmented sub-sectors to slip away from the policy makers' attention because of their small individual relevance. The application of hydrofluorocarbons as blowing agents of polyurethane foams is a good example for this problem (see 3.1.2).

## 2.2 A pragmatic approach on emission estimates

Due to constraints on time and resources this study had to apply a pragmatic approach on some aspects within its scope. In several cases shares of total European emissions had to be assigned to individual countries. Often this was done by means of countries' share of European gross domestic product (GDP). It was decided to use 1993 GDP numbers [EUROSTAT, 1995] instead of more recent data in order to avoid artefacts caused by recent changes of exchange rates between countries which joined the European monetary union and those which preferred to stay outside. It has been demonstrated elsewhere that GDP can be used as a reasonable proxy for the use of fluorocarbons in stable markets [McCulloch et al., 1994]. This approach has obvious deficiencies but is definitely transparent and not data intensive. Due to the same resource constraints some inconsistencies were unavoidable, e.g. when emissions associated with manufacturing and distribution of fluids were assigned to countries irrespective of actual manufacturing capacity or consumption. National activities under the UNFCCC will certainly address these issues more comprehensively.

### 2.3 The baseline scenario

The baseline (business as usual) scenario used for this study allows for autonomous technological improvement, e.g. reduced leakage rates. The baseline scenario also considers policies and measures in place.

### 2.4 Uncertainties of emission factors

The appropriate choice of emission factors probably remains the main problem to derive reasonable base year emissions or future baseline scenarios. The recent efforts under the IPCC/IEA/OECD Greenhouse Gas Emission Inventory Programme reflect this difficulty. In many cases there may now be some consensus of expert opinions on the right emission factor for a certain process. However, some of these emission factors are too low to account for the observed increase of atmospheric concentrations, e.g. in the cases of $SF_6$, HCFC-141b and HCFC-142b with discrepancies of up to 100%. A temporary consensus among a certain group of experts should thus be seen cautiously. In many cases actual uncertainties of emission estimates may still be significantly larger than estimated by an expert group.

### 2.5 Global warming potentials

Global warming potentials (GWPs) are used to compare the radiative impact different greenhouse gases are likely to have on climate over a certain time horizon that is subject to subjective choice. Within the IPCC process commonly values of 20, 100 and 500 years are applied. It was agreed to use 100 year values under the Kyoto Protocol. Two points need to be addressed regarding GWPs. GWPs are not well established material constants. They are undergoing a permanent revision process: underlying spectroscopic data are continuously updated, atmospheric residence times for target species and the reference molecule $CO_2$ are also revised from time to time. The WMO-Ozone Assessment 1998 [WMO, 1999] reports the most recent results of these revision processes. Increases of about 25% of 100 year GWPs for HFCs are not uncommon.

However, it has been agreed that during the first commitment period of the Kyoto Protocol no modifications will be made to GWP values. This study thus continues to use the GWPs from IPCC [1996] to ensure comparability with prior results. Another factor that leads to some uncertainty of our results when expressed as $CO_2$-equivalent emission originates from the assumptions on a mean GWP for a group of applications (see section 8 in the annex to the report). This error can be quite large, e.g. in the semiconductor sector, where many different substances with greatly different GWPs are used.

### 2.6 Selection of key abatement options and cost estimates

This study focuses on the economic evaluation of one or a few key abatement options for each process. It is not a technology survey. Key abatement options are here defined as existing technologies with applicability across a large range of circumstances. Generally associated cost calculations will be conservative, i.e. with a bias towards overestimating cost as newer technologies will often be under development that deliver the same performance at lower costs. Costs reported in this study are 1999 Euros (€) except for final results in Table 36 which are reported as deflated 1990 Euros to ensure direct comparability with the framework study into which these results will feed. Generally, the economics of most abatement options relevant to HFCs, PFCs and $SF_6$ are quite uncertain. This is due to the fact that applications of products differ widely, that energy efficiency issues are involved and because only few exploratory studies have been carried out to date [e.g. Novem/Ecofys, 1997; March, 1998; March, 1999; Ecofys, 1999]. Throughout the study abatement options are labelled with codes like “P1.2.1.” The first letter refers to the gas abated, e.g. “P” standing for PFCs, “H” for HFCs and “S” for $SF_6$. The first number refers to the respective paragraph within chapter 3 i.e. the overall sector. If three numbers are given, the second number refers to the sub-sector. The last number always refers to the specific abatement option aimed at emission reductions in that specific sector / sub-sector.

# 3 Processes, emissions and abatement options

## 3.1 Hydrofluorocarbons (HFCs)

The situation for the use of HFCs is currently very dynamic as a rapid transition is taking place in the field of fluorocarbon applications. The phase out of ozone depleting substances (ODS) like chlorofluorocarbons under the Montreal Protocol has been accomplished by replacing them with HFCs, other organic or inorganic fluids with similar properties or more substantial shifts in technologies. High substitution rates by HFCs are foreseen by many experts in the fields of refrigeration, air conditioning and for blowing agents for the production of thermal insulation foams. Low substitution rates by HFCs are anticipated in other traditional market of fluorocarbons, like aerosol propellants and solvent applications that have already largely shifted to other fluids and technologies.

### 3.1.1 Emission of HFC-23 from the production of HCFC-22

**Background:** Trifluoromethane (HFC-23) is a by-product of the production of $CHClF_2$ (HCFC-22) through over-fluorination. Depending on technology and different process parameters the specific formation rate is reported to vary between 1.5 and 4% if no emission abatement is carried out [Branscome and Irving, 1999]. HCFC-22 is produced both for the end-use market e.g. as refrigerant and as a feedstock for the production of further fluoro-organics e.g. polytetrafluoroethene (PTFE).

**Base year emissions:** Subsequently a global mean emission factor will be derived which will then be applied to the European situation. Production numbers for the western world are reported for the end-use market [AFEAS, 1998] but not for feedstock applications thus making it difficult to properly assign emissions to individual countries. The global emissions are rather well constrained by atmospheric observations [Oram et al., 1998]. They estimate global emissions of 6,400±600 tons in 1990 and 7,300±700 tons in 1995. Branscome and Irving [1999] estimate that the global production of HCFC-22 for end-market and feedstock use was 391,000 tons. Combined with data from Oram et al.

[1998] this corresponds to industry-wide mean emission values of about 2%. This value is used to calculate 1995 emissions by multiplying with the production[1] estimates from Branscome and Irving [1999] which are the only ones available on the national level. Germany is the only EU country[2] for which the installation of an emission abatement in 1995 has been reported in the second national communication (a 50% abatement was assumed in 1995 as the equipment came in line during 1995). In absence of comparable national production data for 1990 the Branscome and Irving [1999] data for 1995 were scaled by a factor of 0.79 to roughly mirror the expansion of global sales of non-feedstock HCFC-22 [AFEAS, 1998]. Two sets of emission estimates for 1995 and 2010 are given in Table 1. Uncertainties are obviously large and need to reduced.

**Table 1 Production estimates of HCFC-22 including feedstock and derived emissions. Values derived and used in this study are based on Branscome and Irving [1999] and uniform emission factors. Estimates[3] in parentheses were provided in or calculated based on a personal communication by N. Campbell and A. McCulloch.**

| | Production in 1995 and 2010 [t / yr] | Emissions of HFC-23 in 1995 [t / yr] | Emissions of HFC-23 in 2010 [t / yr ] | Implicit 1995 emission factor: t HFC-23 / t HCFC-22 produced |
|---|---|---|---|---|
| France | 15,300 (24,500) | 310 (160) | 15 (8) | 0.02 (0.007) |
| Germany | 29,000 (27,000) | 290 (270) | 29 (14) | 0.01 (0.01) |
| Greece | 2,600 (5,000) | 52 (100) | 52 (50) | 0.02 (0.02) |
| Italy | 17,000 (25,000) | 340 (190) | 17 (10) | 0.02 (0.008) |
| The Netherlands | 21,000 (25,000) | 420 (570) | 21(29) | 0.02 (0.023) |
| Spain | 17,000 (16,000) | 340 (560) | 340 (28) | 0.02 (0.035) |
| United Kingdom | 26,000 (36,000) | 520 (1,300) | 140 (65) | 0.02 (0.036) |
| **EU-15** | **127,900 (158,500)** | **2,270 (3,150)** | **614 (204)** | **0.18 (0.20)** |

**Key abatement option:** The abatement of HFC emissions from this source basically involves the destruction of about 200 t / yr concentrated HFC-23 for a typical plant of

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[1] The Branscome and Irving [1999] production estimates are based on values of production capacity of HCFC-22 as estimated by manufacturers and an assumed 85% capacity utilisation.

[2] N. Campbell and A. McCulloch in a personal communication report that in France the active abatement of HFC-23 emissions was already mandatory in 1995.

[3] N. Campbell and A. McCulloch in a personal communication estimated values for 1995 production by assuming that it equalled capacity as reported in the Chemical Economics Handbook of the Stanford Research Institute. Respective emission factors are site specific. Assumptions on the level of abatement of HFC-23 emissions in different countries in 2010 also differ from this study.

10,000 t / yr production capacity. This destruction is typically carried out by thermal oxidation (H1.1). Waste gases from this process need to be treated. A recovery of fluoride is possible. According to expert judgement investment costs for a thermal oxidiser are at €3m per plant with total annual operational costs of €200,000 / yr. The total European investment for the remaining (4 out of 10) European plants without treatment would be about €12m in order to accomplish a 95% abatement of HFC-23 emissions. The respective increase of operation and maintenance costs would thus be roughly €0.8m per year for these 4 plants.

**Baseline scenario:** The Montreal Protocol restricts the consumption of HCFCs in non-feedstock applications. The production remains unregulated. Under the Montreal Protocol consumption of HCFCs in industrialised countries is reduced progressively from an adjusted 1989 reference level after 2004 (by 35%), after 2010 (by 65% ), after 2015 (by 90%) and after 2020 (by 99.5%). The consumption of HCFCs in developing countries is limited to its levels of the year 2015 between 2016 and 2040 [UNEP, 1998a]. Global and European feedstock consumption of HCFCs is likely to expand at a rate well above European mean GDP growth. According to its Common Position (EC 19/1999) the European Union intends to directly control the future production, sales and trade of non-feedstock HCFC. A significant decline of the European production of HCFC-22 is nevertheless not warranted as the new regulation does not cover feedstock, exhibits exemptions, a mandate for future revisions and provisions for exports. For our baseline scenario we thus assume that the production of HCFC-22 remains constant until the end of the first commitment period of the Kyoto Protocol. Emission reductions by 95% were included into the baseline scenario for Germany, the Netherlands, France, Italy and ¾ of the UK production. For the remaining four production plants in Spain, Greece and the United Kingdom abatement has not yet been implemented and is thus not included into the baseline scenario.

### 3.1.2 Production and use of foams

**Background:** The production of foams has remained a very significant application of fluorocarbons after the ban of chlorofluorocarbons. Fluorocarbons are used as blowing agents in a solidifying matrix of a polymer. The main types of closed cell foams are extruded polystyrene (XPS) and polyurethane (PU). Emissions of fluorocarbons occur during the production, and, at a lower rate, during use and disposal of foams. Emissions from a mature bank of foam products can, however, outweigh production losses.

**Base year emissions:** Except for one component foams (OCFs) which are used both in the do-it-yourself and commercial construction segment, there were only a few minor applications of HFCs in the foam sector (integral skin foams, imitation wood) in 1995. Emissions from the use of OCFs amounted to about 4,200 tons of HFCs in 1995 [Mahrenholz, 1999; Öko-Recherche, 1996]. Thereof emissions of 1,700 tons were assigned to Germany [Mahrenholz, 1999; Öko-Recherche, 1996]. The remainder was distributed across the other European countries according to their gross domestic product.

**Key abatement options:** In thermal insulation applications foams often directly compete with other insulation materials. Changes of building standards and customs or minor shifts of costs may significantly influence the pattern of foam consumption. In addition there may be future technological options like vacuum insulation panels or advanced materials that could partly substitute the foam products treated in this chapter.

Although it is recognised that that capture / recovery & re-use options are being investigated at plant level, especially for XPS there is no information on costs and technological viability available at present, for this assessment only options using alternative blowing agents, such as hydrocarbons and $CO_2$ will be considered as available abatement options for the 9 foam market segments. March [1998] did not calculate any cost figures for the abatement of future HFC emissions in the polyurethane sector. To estimate the required investment costs for the conversion into non-HFC blowing agents (mainly hydrocarbon) relative to the HFC solution we here use results from expert interviews (Table 2). The future costs of a full European conversion are lower because a significant share of European plants has already been converted. To calculate the abatement costs in paragraph 4.3 a respective reduction of the required investment and increased product costs is taken into account according to the projected market penetration of HFCs in each field of application (see below). Switching to $H_2O/CO_2$ blown PU spray applications does not require investments for the supplier of polyol and isocyanate components. Because of the higher viscosity of the mixture and changed stream ratios processors of PU spray foam may often not be able to continue to use their old machinery. Due to their small turnover these small enterprises possibly need financial assistance to retrofit their machinery or buy new equipment, which is available at about €10,000 a piece.

One large European producer of XPS (BASF) will soon have converted all of its production lines to $CO_2$ blown XPS foams. Conversion costs and the increases of product costs for this manufacturer's technology are modest (with an investment for conversion of €0.8m per line and small thickness and density penalties). Data for XPS in Table 2 thus only cover the remaining producers for which a conversion is more costly and product penalties are larger (G. Abbott - personal communication).

**Table 2 Number of production plants, investments costs per plant, total European conversion costs, product thickness and density penalties for alternative blowing agent, total increased annual product costs for projected 2010 sales (see below).**

| | number of lines | specific invest-ment | total invest-ment | thickness penalty | density penalty | increase of product costs | code |
|---|---|---|---|---|---|---|---|
| PU appliances | 40 | €2m | €80m | 10% | 0% | €40m / yr | H2.1.1 |
| PU cont panel | 30 | €0.5m | €15m | 10% | 0% | €37m / yr | H2.2.1 |
| PU ff laminate | 40 | €0.5m | €20m | 10% | 0% | €35m / yr | H2.3.1 |
| PU disc. panel[#] | 100 | €0.5m | €50m | 10% | 0% | €26m / yr | H2.4.1 |
| PU pipe | 10 | €0.5m | €5m | 0% | 0% | €0 / yr | H2.5.1 |
| PU spray (to $CO_2$)[*] | 1000 | €0.01m | €10m | 0% | 35% | €31m / yr | H2.6.1 |
| PU OCF | 35 | €0.5m | €18m | 0% | 0% | €0 / yr | H2.7.1 |
| PU blocks & misc | 300 | €0.5m | €150m | 10% | 0% | €26m / yr | H2.8.1 |
| XPS ($CO_2$) non-BASF[§] | 18 | €3.5m | €63m | 10%[@] | 5%[@] | €30m / yr[@] | H2.9.1 |

[#] the number of plants does not include a larger number of small enterprises which are estimated to be responsible for 20% of emissions from this sub-sector.

[*] for PU spray "lines" relates to the final processors which are small enterprises.

[§] BASF lines (which are not included in this table) are assumed to be fully converted by 2002 at low costs.

[@] These values continue to be under debate - they reflect an average of contradicting expert views.

The choice of blowing agent does have some impact on the overall flammability of a foam product, i.e. fluorocarbons increase fire resistance. In many cases flame retardents (which often themselves are not truly environmentally benign) can compensate for the use of hydrocarbons when reformulating to meet fire test requirements.

The hydrocarbons used as alternative blowing agents can contribute to the formation of tropospheric ozone along with a multitude of other sources of so-called volatile organic compounds (VOCs). The respective EU VOC-directive (1999/13/EC) does not cover VOC emissions from foams. However, stricter national regulations could require a post-combustion of plant exhausts from production lines using hydrocarbon blowing agents. This would significantly increase required conversion costs to hydro carbon technology. These potential costs have not been included below.

As a consequence of conversion product costs are here assumed to be affected in mainly two ways: through production related “density penalty” of the foam and a “thickness penalty” due to changes of its insulation performance. The latter concept of a “thickness penalty” is used to estimate changes of product costs due to a varying decrease of insulating efficiency after a change to alternative blowing agents. It assumes that the thickness of insulation materials will be increased to arrive at equal thermal insulating properties. Sometimes these thermal insulating properties will not be critical parameters, e.g. when rigidity or water resistance are more important. In other cases thickness constraints are very strict (e.g. transport refrigeration) and thermal insulation will be to some degree poorer than if HFC-blown foams were used. Increased $CO_2$-emissions from the respective heating or cooling systems would be unavoidable. The shift to non-HFC blowing agents will generally lead to some cost reduction due to lower costs of the blowing agent. The “thickness-penalty” concept thus does not systematically underestimate the increase of product costs. It is an appropriate tool to reduce the complexity of the insulation foam market and to derive indicative cost estimates for the abatement of HFC-emissions from foam applications. Thickness penalty values in Table 2 were derived from expert interviews regarding the future difference of insulating properties of alternatively blown foams relative to HFC-blown foams. It is anticipated that foams blown with liquid HFCs will exhibit comparable insulating properties to CFC- or HCFC-blown foams. The final insulating properties of future foam products are currently not well established at the moment as contradicting views by different manufacturers prevail and process optimisation may lead to performance improvements. The ageing of foams which leads to a deterioration of insulation properties also needs be taken into account. Consistent and reviewed data are currently not available.

**Baseline scenario:** Differing from assumptions by March [1998] we assume that in Europe polyethene and other open cell foams will not be blown by means of halocarbons in 2010 because of higher costs of HFCs. One component foams (OCFs) are assumed to be the exception to this rule. A large share of closed cell foams is nowadays produced by means of hydrochlorofluorocarbons (HCFCs). During recent years the use of carbon-dioxide and hydrocarbons (iso-pentane and cyclo-pentane) has expanded rapidly particularly in the central and northern European rigid foam industry. Under the phase-out regime of the Montreal Protocol HFCs along with alternative substances are potential substitutes for HCFCs. The liquid replacement HFCs (HFC-245fa and HFC-365mfc) are currently not commercially available while gaseous HFC-134a is available and in use in certain applications. In this study it is assumed that liquid HFCs will become available in commercial volumes starting from 2003. If projected demand does not warrant a commercial production certain blends of gaseous HFCs or HFCs and hydrocarbons would be used as blowing agents with poorer insulating properties thus decreasing thickness penalties calculated above.

Table 3 lists the respective data used in this study. Applied emission parameters are as reported by Ashford [1999] and fed into the IPCC/OECD/IEA [1999] inventory exercise. The initial HFC mass content of the formulations are own indicative estimates based on the notion that higher prices of HFCs will lead to somewhat lower specific usage of HFCs as compared to (H)CFCs.

**Table 3 HFC- emission parameters for different rigid foam applications of HFCs. PROD LIFE is the average product life, EF PROD is the emission factor for the production step, EF LIFE refers to the use phase while EF DISP covers the amount of HFCs that can be released from the product at the end of its lifetime.**

| | **PROD LIFE [yr]** | **EF PROD [%]** | **EF LIFE [% / yr]** | **EF DISP [%]** | **HFC[4] cont. formulation [% mass]** |
|---|---|---|---|---|---|
| PU appliances | 15 | 4 | 0.25 | 92 | 7 |
| PU/PIR/Phen ff lamin. | 50 | 10 | 1.5 | 15 | 7 |
| PU disc panel | 50 | 12.5 | 0.5 | 63 | 7[5] |
| PU cont panel | 50 | 7.5 | 0.5 | 68 | 7 |
| PU blocks | 15 | 38 | 0.8 | 49 | 7 |
| PU spray | 50 | 25 | 1.5 | 0 | 12 |
| PU pipe in pipe | 50 | 10 | 0.5 | 65 | 3 |
| PU one component foams | 50 | 100 | 0.0 | 0 | 14 |
| XPS | 50 | 25 | 2.5 | 0 | 12 |

Market data for the European PU and XPS markets were adopted from Jeffs and de Vos [1999] and G. Abbott (personal communication), respectively. Sales data for OCF were taken from Mahrenholz [1999]. On this basis market projections (Table 4) were made for 2010 assuming distinct growth rates for different applications. Phenolics which offer a greatly improved fire resistance relative to PU are not included into these numbers because of their comparatively small absolute relevance (sales of 1,800 t / yr in 1995 [IAL, 1995]).The use of Phenolics will depend on the availability of HFCs and could exhibit significant growth rates. These numbers are indicative because demand for insulation materials is tightly linked to building and energy efficiency standards. Mean growth rates between 1990 and the present have been significantly higher mainly driven

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[4] A reviewer commented that specific HFC usage would be too high if manufacturers decided to use blends of roughly 50% HFCs and 50% hydrocarbons. The authors feel that it is difficult to take into account such decisions in the baseline scenario. The decision to move to these 50/50 blends would have significant impact on our cost estimates as projected HFC emissions would be cut by 50% against our baseline but also differences in insulation values would narrow between blend blown and HC blown foams. Differences in plant conversion costs would also probably narrow due to required fire protection.

[5] One reviewer pointed out that a significant part of the discontinuous panel market is likely to switch to HFC-134a instead of liquid HFCs. These applications would use formulations with HFC mass contents of 3%. Respective foam products are likely to exhibit an insulation performance comparable or poorer to HC blown foams. Our cost calculations do not consider this projected development.

by rapidly rising demand from the construction sector in re-unified Germany which currently absorbs about 1/3 of European sales of thermal insulation products [IAL, 1995].

**Table 4 European foam market in 1998 and 2010 and assumed growth rate[6].**

| | market size in 1998 [t / yr] | market size in 2010 [t / yr] | applied growth rate [% / yr] |
|---|---:|---:|:---:|
| PU appliances | 177,000 | 199,000 | 1.0 |
| PU/PIR ff lamin. | 123,000 | 175,000 | 3.0 |
| PU disc panel | 92,000 | 13,100 | 3.0 |
| PU cont panel | 130,000 | 185,000 | 3.0 |
| PU blocks | 37,000 | 53,000 | 3.0 |
| PU spray | 39,000 | 44,000 | 1.0 |
| PU pipe in pipe | 31,000 | 44,000 | 3.0 |
| PU OCF | 30,000 | 34,000 | 1.0 |
| XPS | 123,000 | 175,000 | 3.0 |
| **TOTAL** | **782,000** | **1,041,000** | **2.3** |

Calculated estimates for the aggregate European emissions in 2010 are given in Table 5. These values include emissions during production and use only. The appropriate disposal of foam products is a matter of controversial debate. However, it will not have a significant impact on the emissions of HFCs by 2010. A European market survey on insulation materials [IAL-Consultants, 1995] was used to derive emission estimates for the individual countries. Missing data for Greece were estimated using the same per-capita data as calculated for Spain. The aggregate data for the Benelux-countries were split up assuming constant per-capita consumption across all three countries.

In order to assign emissions to countries we made the simplified assumption that emissions occur in the country of apparent consumption. This will often not be the case, as foam products are traded among EU-countries, exported from and imported to the EU as raw foams or in products. Apart from consumption levels countries are treated equally, i.e. the same market penetration of HFCs is assumed for each application in each country. This is currently obviously not the case but trade in products,

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[6] It was suggested that higher growth rates (+6...10% yr$^{-1}$) should be used for projections in the construction sector. However, additional growth in this sector is likely to be connected to policies to reduce the heating demand of buildings (construction & retrofitting).

technological dissemination and European standardisation will certainly lead to more uniformity of insulation products across Europe.

**Table 5 Projected market penetration[7] of HFCs, consumption of HFCs in specific applications and projected emissions from the production and use of foams (2010).**

| | HFC market penetration [%] | HFC use [t / yr] | Emissions Production [t / yr] | emissions use [t / yr] |
|---|---|---|---|---|
| PU appliances | 30 | 4,190 | 170 | 70 |
| PU/PIR ff lamin. | 50 | 6,140 | 610 | 640 |
| PU disc panel | 70 | 6,430 | 800 | 220 |
| PU cont panel | 20 | 2,590 | 190 | 90 |
| PU blocks | 70 | 2,580 | 970 | 140 |
| PU spray | 90 | 4,750 | 1,190 | 500 |
| PU pipe in pipe | 50 | 660 | 70 | 20 |
| PU OCF | 90 | 4,260 | 4,260 | 0 |
| XPS | 60 | 12,580 | 3,140 | 2,200 |
| **TOTAL** | | **44,180** | **11,400** | **3,890** |

### 3.1.3 Refrigeration and stationary air conditioning

**Background:** Fluorocarbons have long been used as safe and efficient fluids in refrigeration and air-conditioning. Reliable and transparent quantitative information on the use of refrigerants is hard to find for most countries of the EU. Öko-Recherche [1996] presented a distribution of refrigerants in different applications in Germany. March [1999] derived a similar data-set for Great Britain. Palandre et al. [1998] have compiled a very detailed study on the current and future use of refrigerants in France. The French data are used here to derive data for the applications in other countries. An estimate of the banked amounts of refrigerants in different sectors is derived by scaling the French numbers according to other countries' GDP[8]. This is done against the background of a virtual absence of comparable data for other countries in the open literature. Evidently not all countries exhibit the same patterns of refrigerant use as France, e.g. when it comes to air conditioning or the food and agricultural industry

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[7] It was cautioned that projected values for HFC penetration are likely to be too high for spray foams, appliances and pipe in pipe.

[8] Concerns have been expressed about the accuracy of these extrapolations but it was also conceded that the required market data are currently unavailable.

(compare 4.2.1). These inherent errors have to be tolerated until better data on banked refrigerants in European countries become available. The estimated numbers are corrected for the actual share of HFCs of all banked refrigerants (Table 6).

**Table 6 Banked amount of HFC refrigerant in different applications[9] [tons] in 2010.**

| | **DOM REF** | **COM REF** | **TRANS REF** | **FA IND** | **GEN IND** | **AC WAT** | **AC DX** | **TOTAL** |
|---|---|---|---|---|---|---|---|---|
| Austria | 300 | 400 | 400 | 300 | 200 | 100 | 200 | **1,700** |
| Belgium | 400 | 500 | 500 | 300 | 200 | 100 | 300 | **2,300** |
| Denmark | 300 | 300 | 300 | 200 | 100 | 100 | 200 | **1,300** |
| Finland | 200 | 200 | 200 | 100 | 100 | 100 | 100 | **800** |
| France | 2,300 | 2,900 | 3,000 | 2,000 | 1,200 | 800 | 1,600 | **15,100** |
| Germany | 3,600 | 4,400 | 4,600 | 3,100 | 1,800 | 1,200 | 2,400 | **18,200** |
| Greece | 100 | 200 | 200 | 100 | 100 | 100 | 100 | **900** |
| Great Britain | 1,800 | 2,100 | 2,300 | 1,500 | 900 | 600 | 1,200 | **11,300** |
| Ireland | 100 | 200 | 200 | 100 | 50 | 50 | 100 | **800** |
| Italy | 1,800 | 2,300 | 2,400 | 1,600 | 900 | 600 | 1,300 | **11,900** |
| Luxembourg | 20 | 30 | 30 | 20 | 10 | 10 | 20 | **140** |
| Netherlands | 600 | 700 | 800 | 500 | 300 | 200 | 400 | **3,000** |
| Portugal | 200 | 200 | 200 | 100 | 100 | 100 | 100 | **1,000** |
| Spain | 900 | 1,100 | 1,200 | 800 | 400 | 300 | 600 | **5,800** |
| Sweden | 300 | 400 | 500 | 300 | 200 | 100 | 200 | **1,800** |
| **EU-15** | **12,800** | **15,700** | **16,800** | **11,000** | **6,400** | **4,400** | **8,700** | **75,800** |

**Table 7 Parameters (mainly 2010) used for calculations for different applications.**

| | **DOM REF** | **COM REF** | **TRANS REF** | **FA IND** | **GEN IND** | **AC WAT** | **AC DX** |
|---|---|---|---|---|---|---|---|
| EF during product life [% / yr] | 1 | 10 | 15 | 10 | 10 | 10 | 10 |
| EF decommissioning [% of initial charge] | 80 | 10 | 50 | 10 | 10 | 10 | 10 |
| Mean lifetime of equipment [years] | 15 | 10 | 10 | 25 | 25 | 25 | 15 |
| 2010 HFC-share of refrigerant bank [%] | 45 | 60 | 70 | 20 | 35 | 40 | 40 |
| 2030 HFC-share of refrigerant bank [%] | 45 | 85 | 100 | 50 | 75 | 95 | 95 |

The sectors comprise domestic refrigeration, commercial refrigeration, food and agricultural and general industrial refrigeration, transport refrigeration including

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[9] Domestic refrigeration (DOM REF), commercial refrigeration (COM REF), food and agricultural (FA IND) and general industrial refrigeration (GEN IND), transport refrigeration including merchant and naval ships (TRANS REF) and stationary air conditioning using water chilling (AC WAT) and distributed technology (AC DX)

merchant and naval ships[10] and stationary air conditioning using water chilling and distributed technology. Emission factors, equipment lifetimes and estimated values for the penetration of HFCs in 2010 and 2030 and other relevant parameters are given in Table 7. Values are based on expert interviews and published data in Öko-Recherche [1996], March [1998], March [1999] and Palandre et al. [1999] and represent a fairly conservative view of the technological potential. Despite certain regional pattern regarding the use of non-fluorocarbons in certain applications all countries are treated alike in this study. The use of mobile air-conditioning was estimated separately in a bottom-up approach (see next paragraph), because of the application’s quantitative relevance and the availability of data.

**Base year emissions:** There was no significant use of HFCs in refrigeration and air conditioning in 1990. In 1995 HFCs use was expanding. Öko-Recherche [1996] estimates that in Germany in 1995 about 190 tons of HFCs were emitted from this field of application. For the other countries of the EU we scaled this value according to their GDP. EU-wide emissions of 675 tons are estimated for 1995.

**Key abatement options:** A significant number of options to reduce halocarbon emissions from this sector has been described [e.g. Novem/Ecofys, 1997; March, 1998]. Due to the inherent complexity of the sector there is little transparent and representative information on the costs of these abatement options. It would go far beyond the scope of this study to comprehensively fill this gap. Based on expert interviews own indicative cost estimates were derived that are consistent with the sub-division of applications and the emission model used in this study. For this latter reason we use specific mean cost values per ton of installed HFC (Table 8) and calculate abatement costs from mean changes of these specific costs per application and abatement option (Table 9). This approach consciously ignores much of the technological complexity of this field. Values in both tables are first estimates and may require future revisions.

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[10] One reviewer remarked that emissions from ships would largely occur in international waters and thus not be directly attributable to individual countries. This problem is comparable to the issue of bunker fuels.

**Table 8 Assumptions[11] on specific mean costs (investment for equipment, energy costs and maintenance costs) per ton of installed HFC per applications. Values are indicative and require future improvement.**

| application | spec. inv. for equip. [€ / tons HFC] | spec. energy costs [€ / tons HFC / yr] | spec maint. costs [€ / tons HFC / yr] |
|---|---:|---:|---:|
| Domestic Refrigeration | 1,500,000* | 800,000* | 0* |
| Commercial Refrig. | 500,000 | 70,000 | 10,000 |
| Food & Agro Industry | 200,000 | 100,000 | 10,000 |
| General Industry | 200,000 | 100,000 | 10,000 |
| Transport Refrig. | 250,000 | 120,000 | 10,000 |
| Stationary Airco DX | 400,000 | 70,000 | 10,000 |
| Stationary Airco Water | 200,000 | 70,000 | 10,000 |
| Mobile Airco | 250,000* | 60,000* | 15,000* |

* Values are reported for illustrative purposes only and are not used for cost calculations.

The costing approach for DOM REF is different as equipment costs and performance basically remain unaffected of conversion. Instead, conversion costs of €1m per factory were assumed. Costs for the recovery of used refrigerant were considered for domestic refrigeration (at costs of €15 per appliance) only. Recycling equipment was assumed to be available at €10,000 per piece with 1,000 pieces required to cover Europe. By default, for other applications recovery of 80% of the initial charge was assumed to take place at the end of life. In most applications in publicly accessible areas (e.g. commercial refrigeration) the use of an alternative refrigerant beyond a threshold charge (the value may vary between countries) will involve secondary cycles and water cooled condensing units which significantly increase both investment costs and energy costs. In other cases where public access is restricted (food & agricultural and general industry) secondary cycles are usually not required. In these cases fewer safety precautions have to be taken. Safety concerns vary significantly between different countries and industries. The use of ammonia is very common in certain countries while strongly restricted in others. A successful implementation of a strategy that promotes alternative refrigerants requires the full acceptance of these compounds by stake holders such as end-users, regulators and insurance companies.

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[11] Concerns about the accuracy of these estimates have been expressed but it was also conceded that the required data are currently unavailable. The authors of this study would like to emphasise that they have clearly stated the uncertainties and limitations of their approach.

**Table 9 Assumptions[12] on relative cost increases[13] and respective emission reduction. Estimates for domestic refrigeration and mobile air conditioning were not derived using this methodology. Numbers are indicative and require further improvement.**

| Measure | code | increase of investment costs [%] | incr. of energy costs [%] | increase of maintenance costs [%] | emission reduction [%] |
|---|---|---|---|---|---|
| Commercial refrig: hydrocarbons a. NH3 | H3.2.1 | 20 | 20 | 20 | 100 |
| Commercial refrigeration: leakage reduction | H3.2.2 | 2 | 0 | 50 | 40 |
| Industrial food refrig.: hydrocarbons a. NH3 | H3.3.1 | 20 | -5 | 20 | 100 |
| Industrial food refrig: leakage reduction | H3.3.2 | 2 | 0 | 50 | 40 |
| Industrial refrig.: hydrocarbons a. NH3 | H3.4.1 | 20 | -5 | 20 | 100 |
| Industrial refrigeration: leakage reduction | H3.4.2 | 2 | 0 | 50 | 40 |
| Transport refrigeration: leak reduction | H3.5.1 | 5 | 0 | 50 | 40 |
| Stationary air condit. DX: hydrocarbons | H3.6.1 | 20 | 20 | 20 | 100 |
| Stationary air condit. DX: leak reduction | H3.6.2 | 2 | 0 | 50 | 40 |
| Stationary air condit. chiller: HC &NH3 | H3.7.1 | 10 | 0 | 20 | 100 |
| Stationary air condit. chiller: leak reduct. | H3.7.2 | 2 | 0 | 50 | 40 |

Further details on cost estimates are described in paragraph 4.3. It needs to be emphasised that our cost estimates are indicative and based on the assumption that conversion measures to alternative refrigerants are carried out evolutionary as old refrigeration and air conditioning units have to be replaced. The effect of increases or decreases of the energy consumption on $CO_2$ emissions have been estimated but not been included into the cost estimates as it was found that for the given set of parameters and the European electricity grid the increase was less than 30% of total equivalent $CO_2$ emissions due to leakage HFCs emissions even in the worst cases (e.g. commercial refrigeration). It should nevertheless be kept in mind that under different circumstances secondary refrigeration and air conditioning systems could have an increasing net effect on equivalent greenhouse gas emissions if compared to primary systems using HFCs. This issue requires further analysis taking into account the large national differences in the carbon intensity of electricity generation within the EU and differences in performance between different system types within the product-groups.

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[12] Concerns have been expressed about the accuracy of these estimates but it was also conceded that the required data are currently unavailable. The authors of this study would like to emphasise that they have clearly stated the uncertainties and limitations of their approach.

[13] It has been pointed out by several reviewers that these cost estimates may be too conservative for alternative systems, i.e. that cost have been shown to be lower or even negative in various cases.

**Table 10 Emissions of HFC refrigerant from different applications[14] in 2010 [tons / yr]. Decommissioning is only included for domestic refrigeration.**

| | DOM REF | COM REF | TRANS REF | FA IND | GEN IND | AC WAT | AC DX | TOTAL |
|---|---|---|---|---|---|---|---|---|
| Austria | 10 | 40 | 60 | 30 | 20 | 10 | 20 | **180** |
| Belgium | 20 | 50 | 80 | 30 | 20 | 10 | 30 | **240** |
| Denmark | 4 | 30 | 50 | 20 | 10 | 10 | 20 | **150** |
| Finland | 2 | 20 | 30 | 10 | 10 | 10 | 10 | **90** |
| France | 230 | 290 | 460 | 200 | 120 | 80 | 160 | **1,530** |
| Germany | 50 | 440 | 700 | 310 | 180 | 120 | 240 | **2,030** |
| Greece | 10 | 20 | 30 | 10 | 10 | 10 | 10 | **90** |
| Great Britain | 170 | 210 | 340 | 150 | 90 | 60 | 120 | **1,150** |
| Ireland | 10 | 10 | 20 | 10 | 4 | 3 | 10 | **60** |
| Italy | 180 | 230 | 360 | 160 | 90 | 60 | 130 | **1,210** |
| Luxembourg | 1 | 3 | 5 | 2 | 1 | 1 | 2 | **15** |
| Netherlands | 10 | 70 | 110 | 50 | 30 | 20 | 40 | **330** |
| Portugal | 20 | 20 | 30 | 10 | 10 | 10 | 10 | **110** |
| Spain | 90 | 110 | 170 | 80 | 40 | 30 | 60 | **580** |
| Sweden | 10 | 40 | 70 | 30 | 20 | 10 | 20 | **200** |
| **EU-15** | **810** | **1,570** | **2,520** | **1,100** | **640** | **440** | **870** | **7,940** |

**Baseline scenario:** Some types of equipment still using CFCs and HCFCs have a rather long lifetime. The bank of HFCs will thus be roughly 50% mature in 2010. Emission estimates for 2010 can be found in Table 10. These emission levels are expected to grow until maturity of the bank is reached and decommissioning losses become relevant for applications other than domestic refrigeration. It is important to note that TRANS REF is projected to become the main emitter within this group due to large estimated banks in merchant ships.

### 3.1.4 Mobile air conditioning

**Background:** Mobile air conditioning is one of the major sources of fluorocarbon emissions due to rather large specific leakage rates. Emissions are dependent on multiple factors which are quite uncertain. Among them are: number of new cars in each year and

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[14] Domestic refrigeration (DOM REF), commercial refrigeration (COM REF), food and agricultural (FA IND) and general industrial refrigeration (GEN IND), transport refrigeration including merchant and naval ships (TRANS REF) and stationary air conditioning using water chilling (AC WAT) and distributed technology (AC DX)

each country, trends of the share of cars with air conditioning, trends of typical charge per air conditioning system, trends of mean annual leakage rates and trends of mean lifetime of cars and air conditioning system.

**Base year emissions:** While HFCs were not in use in 1990, air conditioners in new cars are generally filled with HFC-134a since about 1993. In this study passenger cars and utility vehicles were not treated separately because of the minor relevance of the latter within the EU. Estimations are based on European new vehicle registration data (1995-1998) provided by the European Automobile Manufacturer Association (ACEA). To calculate 1995 emissions a leakage rate of 15% / yr is applied [Öko-Recherche, 1999] to the estimated bank of HFC-134a in mobile air conditioning equipment (Table 11).

**Key abatement options:** Three different abatement options were considered. The first (code H4.1) involves the introduction of $CO_2$ high-pressure air conditioning systems [Wertenbach and Caesar, 1998] which could start in 2004. The extra investment is estimated to be roughly €50 per vehicle. Operating cost (basically energy) is expected to be comparable to conventional systems. The second abatement option (code H4.2) covers a continuous leakage rate reduction down to 5% / yr. We estimate that this modification may cost €10 per car. The cost of the third option (code H4.3), the recovery of 80% of the remaining refrigerant charge at the end of life of the vehicle is estimated to cost about €10 per car. Partly, this last option could be implemented through the new EC "End of life of vehicles"-directive, which covers the recovery of fluids from old vehicles. The total extra-investment for new cars in 2010 would be €100m / yr and additional costs for a recovery of HFCs at the end of life of vehicles in 2010 would be near €70m.

**Baseline scenario:** It is assumed that alternative refrigerants do not play a significant role in mobile air conditioning until 2012. Based on estimates made by Öko-Recherche [1996] it is assumed that the average amount of HFC per AC-unit linearly decreases from 0.8 kg to 0.6 kg between 1993 and 2012. The effective mean leakage rate is assumed to decrease from 15% / yr to 10% / yr over the same period[15]. Decommissioning is assumed to release 50% of the full charge. A constant lifetime of 12 years for vehicle and AC equipment is assumed. The number of new vehicles per year is assumed to be sustained at the mean level of the period 1995-1998. The share of new vehicles equipped with AC is estimated to have increased from 10% to 50% from 1993 to 1997 and assumed to further increase by 2% / yr thereafter. Emission estimates are given in Table 11.

**Table 11 Estimates of bank of HFC-134a and leakage and decommissioning emissions from mobile AC systems in passenger and utility vehicles.**

| | **Bank HFC-134a [t]** | | **Leakage Emission [t / yr]** | | **Decommissiong Emissions [t / yr]** | |
|---|---|---|---|---|---|---|
| | **1995** | **2010** | **1995** | **2010** | **1995** | **2010** |
| Austria | 130 | 1,660 | 20 | 220 | 0 | 80 |
| Belgium | 180 | 2,340 | 30 | 320 | 0 | 110 |
| Denmark | 70 | 860 | 10 | 130 | 0 | 40 |
| Finland | 40 | 590 | 10 | 80 | 0 | 30 |
| France | 910 | 11,070 | 160 | 1,600 | 0 | 550 |
| Germany | 1,610 | 20,280 | 260 | 2,650 | 0 | 910 |
| Greece | 60 | 850 | 10 | 110 | 0 | 40 |
| Great Britain | 950 | 12,100 | 160 | 1,660 | 0 | 570 |
| Ireland | 50 | 710 | 10 | 100 | 0 | 40 |
| Italy | 890 | 11,940 | 140 | 1,570 | 0 | 540 |
| Luxembourg | 10 | 180 | 0 | 20 | 0 | 10 |
| Netherlands | 220 | 2,810 | 40 | 400 | 0 | 140 |
| Portugal | 100 | 1,280 | 20 | 230 | 0 | 80 |
| Spain | 430 | 5,760 | 80 | 860 | 0 | 300 |
| Sweden | 90 | 1,210 | 10 | 160 | 0 | 60 |
| **EU-15** | **5,740** | **73,630** | **960** | **10,120** | **0** | **3,480** |

### *3.1.5 Other sources*

**Background, base year emissions:** In 1990 and 1995 there was practically no use of HFCs for solvent applications, fire-fighting, metered dose inhalors (MDIs) in any of the EU-countries [March, 1998]. About 1,000 tons may have been used for aerosol applications in 1995 [March, 1998].

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[15] One reviewer suggested that for the year 2010 a lower baseline emission factor of 5%/yr should be used in this study. The authors of this study however believe that to achieve this goal further action is required.

**Key abatement options:** These applications of HFCs involve many factors that go far beyond economic criteria. Despite their potentially large contribution to emissions in 2010, this study considers only a 30% reduction of projected HFC use for general aerosol usage [March, 1998] through substitution with non HFC-propellants. Respective cost data were also taken from March [1998]. General aerosol applications and solvents still await a thorough assessment in respect to projected consumption and abatement options. Regarding MDIs Öko-Recherche [1999] estimates that only 25% of current use is related to emergency therapy and the treatment of children and elderly for which MDIs are essentials[16]. Due to companies' price policies price differences[17] between MDIs and DPIs vary greatly for different countries and specific drugs (€0 in Germany and about €4 in the UK [calculated after March [1999] per average inhaler system containing 17 g of HFC).

**Baseline scenario:** For 2010 we follow March [1998] in their assumption that 40% of the 1996 use of HCFC-141b (6,000 tons / yr) as solvent will be taken up by HFCs. Shares of solvent consumption were assigned to countries according to their GDPs which is a simplification as for example Germany banned fluorocarbons in solvent applications when phasing out CFCs and HCFCs. To estimate HFC emissions from fire fighting applications a bank of 4,000 tons within EU-15 in 2010 was assumed corresponding to a 25% substitution rate of halons in new equipment [March, 1998]. The bank was distributed across countries according to GDP. An emission rate of 3% / yr due to use and maintenance was assumed. By applying the projected German per capita consumption of HFCs in MDI [Öko-Recherche, 1999] to the other EU countries, it is estimated that total emissions from this application will be 1,700 tons / yr in 2010. The 5,400 tons / yr consumption of HFCs in aerosol applications as projected (calculated from data reported by March [1998]) for 2010 is again divided according to GDP. Results for all applications are given in Table 12.

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[16] One reviewer pointed out that this estimate requires further elaboration.

[17] One reviewer emphasised that prices of pharmaceutical products are strongly influenced by government controls. This implies that product prices may not be useful to assess abatement costs of HFC emissions from this sector.

**Table 12 Estimated emissions of HFCs from solvent use, fire-fighting-applications, metered dose inhalors (MDIs) and aerosol applications in 2010 [tons / yr].**

| | Solvent use | Fire-fighting applications | MDIs | Aerosol applications |
|---|---|---|---|---|
| Austria | 60 | 3 | 30 | 140 |
| Belgium | 70 | 4 | 50 | 170 |
| Denmark | 50 | 2 | 20 | 110 |
| Finland | 30 | 1 | 20 | 70 |
| France | 440 | 22 | 260 | 980 |
| Germany | 670 | 33 | 360 | 1,500 |
| Greece | 30 | 1 | 50 | 60 |
| Great Britain | 330 | 16 | 260 | 740 |
| Ireland | 20 | 1 | 20 | 40 |
| Italy | 350 | 17 | 260 | 780 |
| Luxembourg | 10 | 0.2 | 0 | 10 |
| Netherlands | 110 | 5 | 70 | 240 |
| Portugal | 30 | 1 | 40 | 70 |
| Spain | 170 | 8 | 180 | 370 |
| Sweden | 60 | 3 | 40 | 150 |
| **EU-15** | **2,400** | **120** | **1,700** | **5,400** |

### *3.1.6 Manufacturing and distribution losses*

**Background, base year emissions and baseline scenario:** As pointed out by Gamlen et al. [1996] and Midgley and McCulloch [1999] diffusive losses of about 2% commonly occurred for chloroflorocarbons (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 no indication that respective loss rates associated with manufacturing, packaging and distribution are significantly lower for HFCs. For this assessment a conservative estimate of 2% is used, actual values could be considerably higher. Total emissions are broken up according to countries' GDP. Our estimates thus do not reflect national regulations or particular production sites. It is assumed that annual sales of HFCs within the European Union were 0 tons in 1990, 25,000 tons in 1995 and will be 100,000 tons in 2010 (based on estimates in March [1998]).

**Key abatement options:** No abatement options for this source were analyses in this study. More reliable quantitative information on this source of emissions and their abatement are clearly needed.

## 3.2 Sulphur hexafluoride

For $SF_6$ rather reliable sales numbers [SPS, 1997] and precise observations of the atmospheric accumulation rate [Maiss et al., 1996] exist at the same time. Both together lead to a discrepancy which leaves about 50% of inferred global emissions unexplained by bottom-up studies [see Maiss and Brenninkmeijer, 1998; Harnisch and Prinn, 1999]. This challenges reported emission estimates. This study does not attempt to resolve this discrepancy. Readers should still be aware that one or several sources of $SF_6$ are potentially severely underestimated.

### 3.2.1 Magnesium production

**Background:** The casting and production of primary and secondary magnesium (Table 13) are well known sources of atmospheric $SF_6$. Reported values of specific use or emissions of $SF_6$ per mass unit magnesium vary greatly [Palmer, 1999]. For this study a uniform value of 2 kg $SF_6$ per ton of processed metal was adopted. Future research may provide more specific data.

**Base year emissions:** Economic activity data for primary and secondary magnesium were provided by the United States Geological Survey [Kramer, 1995; Kramer, 1996; Kramer, 1997, Kramer 1998]. Casting data were provided by the Committee of Associations of European Foundries (CAEF) [CAEF, 1997; CAEF - personal communication]. Some countries did not report casting data for 1990, others report aggregate numbers for aluminium and magnesium casting. Aluminium casting generally by far outweighs magnesium. In case of aggregate reporting a share of 2% magnesium was applied to obtain proxy data for these countries. In case of missing data for 1990 reported values for 1994 were used. While globally magnesium primary production is expanding, a declining trend is observed for the European industry. Casting of magnesium on the other hand is rapidly expanding (e.g. by 60% from 1997 to 1998 to

11,000 tons in Germany [VDI, 1999]) thus increasing imports of magnesium to the EU.

**Abatement options:** To minimise the specific use of $SF_6$ per ton of magnesium promises significant reduction potential relative to 1990 and 1995 base year levels [Palmer, 1999]. Global sales data of $SF_6$ into the magnesium sector do not suggest that any significant use changes had taken place until 1996 [SPS, 1997]. The obvious option (code S1.1) to fully abate emissions from this source would be to completely switch to $SO_2$ as protection gas. $SO_2$ was the substance used traditionally for this purpose. Due to the toxicity of $SO_2$ the replacement $SF_6$ is now used much more widely. Based on numbers in CAEF [1997] we estimate that in Europe in addition to primary and secondary smelters there are about 100 foundries which are active in casting magnesium. An investment of €100,000 per foundry to switch to $SO_2$ (potentially including a modified gas supply system, improved ventilation and gas warning systems) would lead to total conversion costs of €10m. It should be kept in mind that many foundries are small and medium enterprises which may require financial assistance for this conversion process. The primary and secondary smelters would probably require a significantly higher investment (indicative number of €1m). It is likely that operation and maintenance costs would remain roughly constant after a conversion as $SF_6$ is a rather expensive substance in comparison to $SO_2$. More detailed information on abatement costs is clearly needed. It should be kept in mind that very significant reduction of the specific usage of $SF_6$ in many casting application can also be accomplished through improved process management at very low costs.

**Baseline scenario:** To project emissions in 2010 it is assumed that primary and secondary magnesium production remains on 1995 levels while the amount of magnesium used for casting triples from 1995 levels. Emission factors are assumed to remain constant at 2 kg per ton of processed metal. See Table 14 for results.

**Table 13 Estimated production and casting of primary, secondary magnesium in tons of metal per year.**

| | Primary Mg | | Secondary Mg | | Casting | |
|---|---|---|---|---|---|---|
| | **1990** | **1995** | **1990** | **1995** | **1990** | **1995** |
| Austria | 0 | 0 | | | 95 | 1,467 |
| Belgium | 0 | 0 | | | 3 | 1 |
| Denmark | 0 | 0 | | | 0 | 0 |
| Finland | 0 | 0 | | | 69 | 80 |
| France | 14,000 | 14,450 | | | 591 | 591 |
| Germany | 0 | 0 | | | 7,029 | 4,024 |
| Great Britain | 0 | 0 | 800 | 1,000 | 2,220 | 2,364 |
| Italy | 5,730 | 0 | | | 1,600 | 2,100 |
| Netherlands | 0 | 0 | | | 252 | 327 |
| Portugal | 0 | 0 | | | 108 | 231 |
| Spain | 0 | 0 | | | 1,710 | 2,034 |
| Sweden | 0 | 0 | | | 1,000 | 1,800 |
| **EU-15** | **19,730** | **14,450** | **800** | **1,000** | **14,678** | **15,019** |

**Table 14 Emissions of $SF_6$ associated with the production and casting of primary and secondary magnesium.**

| | Estimated emission in 1990 [t / yr] | Estimated emission in 1995 [t / yr] | Projected Emission in 2010 [t / yr] | Projected 2010 emission in MT $CO_2$ eq. / yr |
|---|---|---|---|---|
| Austria | 0.2 | 3 | 9 | 0.2 |
| Belgium | 0 | 0 | 0 | 0.0 |
| Denmark | 0 | 0 | 0 | 0.0 |
| Finland | 0.1 | 0 | 0 | 0.0 |
| France | 29 | 30 | 32 | 0.8 |
| Germany | 14 | 8 | 24 | 0.6 |
| Great Britain | 6 | 7 | 16 | 0.4 |
| Italy | 15 | 4 | 13 | 0.3 |
| Netherlands | 0.5 | 0.7 | 2 | 0.0 |
| Portugal | 0.2 | 0.5 | 1 | 0.0 |
| Spain | 3 | 4 | 12 | 0.3 |
| Sweden | 2 | 4 | 11 | 0.3 |
| **EU-15** | **71** | **61** | **121** | **2.9** |

### 3.2.2 Manufacture and use of gas insulated switchgear (GIS)

**Background:** Emission estimates of $SF_6$ from the electrical sector are globally rather uncertain. The electricity sector during recent years absorbed about 80% of global $SF_6$ sales according to a survey among manufacturers [SPS, 1997]. Maiss and

Brenninkmeijer [1998] suggest that this fraction may be an overestimate and propose a global value of 50-60 %. Most of this $SF_6$ is banked in gas insulated switchgear (GIS) and similar equipment used by utilities in their high voltage distribution networks. Emission factors for this bank are not known well enough to estimate emissions. Often a substance flow approach is thus used instead of a true bottom-up method. For the European situation it is important to take into account sales of $SF_6$, exports and imports of $SF_6$, banked $SF_6$ as well as exports and imports of $SF_6$ banked in or delivered together with equipment if emissions are to be inferred using a substance flow approach. Within the EU significant industry efforts have recently been undertaken to estimate emission of $SF_6$ associated with the production and use of electric switchgear.

**Table 15 Estimated amounts of $SF_6$ purchased for the manufacture erection and testing of GIS and estimated emssions in 1995.**

| | **Estimated amount of $SF_6$ purchased for GIS [t / yr]** | **Emissions during manufacturing & erection[18] [t / yr]** | **Emission in MT $CO_2$ eq. / yr** |
|---|---|---|---|
| Austria | 0 | 0 | 0.0 |
| Belgium | 0 | 0 | 0.0 |
| Denmark | 0 | 0 | 0.0 |
| Finland | 0 | 0 | 0.0 |
| France | 350 | 44 | 1.0 |
| Germany | 333 | 42 | 1.0 |
| Greece | 0 | 0 | 0.0 |
| Great Britain | 100 | 13 | 0.3 |
| Ireland | 0 | 0 | 0.0 |
| Italy | 110 | 14 | 0.3 |
| Luxembourg | 0 | 0 | 0.0 |
| Netherlands | 43 | 5 | 0.1 |
| Portugal | 0 | 0 | 0.0 |
| Spain | 26 | 3 | 0.1 |
| Sweden | 28 | 4 | 0.1 |
| **EU-15** | **990** | **124** | **3.0** |

**Base year emissions:** European sales of $SF_6$ in 1995 have been estimated to be in the range of 2,400-2,800 tons [Maiss and Brenninkmeijer, 1998]. Part of this total was used

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[18] It was pointed out by one reviewer that commonly only a fraction of emission during erection occurs in the country where the manufacturer is located because GIS are exported. A significant part of these erection losses occurs outside of the EU. The authors of this study caution that sometimes $SF_6$ for exported

by manufacturers and users of gas insulated switchgear. According to information from the European Electricity Supply Industry [CAPIEL/UNIPEDE, 1998] European GIS manufacturers in 1995 bought about 1,250 tons for testing and delivery of GIS for the European (1/3) and export market (2/3), thereof about 1,000 tons within EU-15. In a personal communication CAPIEL has provided the a break-up of this sum across EU-countries (Table 15). According to CAPIEL/UNIPEDE [1998] in 1995 about 12.5% of purchased $SF_6$ was emitted during manufacture, erection and testing of GIS. To calculate respective emissions (Table 16) this uniform emission factor was used in this study across all countries in which GIS manufacturers are located.

Neumann [1999] (based on an unpublished UNIPEDE survey) estimates that the European bank of $SF_6$ is about 3,400 tons in 1995 and also reported a break-up across countries (Table 16). Neumann [1999] reported emission factors for the use of GIS in 1995. These factors can vary significantly depending on the type of equipment in use and on how maintenance is carried out. Calculated Emissions are also given in Table 16.

About 10-20% of installed GIS-equipment belongs to large companies e.g. in the chemical or aluminium industry and may thus escape surveys covering the electrical utilities. If recycling equipment for $SF_6$ is either not available or not used such companies could exhibit significantly higher loss rates of banked $SF_6$ than those cited above and thus contribute over-proportionate to emissions. It should also be noted that emission rates have apparently significantly declined during the 1990's due to greater awareness and improved handling procedures.

**Key abatement option:** The effective loss rates presented in Table 16 clearly suggest that potential still exists for a reduction of leakage rates in certain countries. The same probably applies to the equipment manufacturers for which country specific loss rates are unfortunately not available. Generally the availability of better recovery equipment (with higher flow rates at low pressures) and the allocation of more time for testing, erection and maintenance could significantly decrease emissions. The economics of such

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equipment will be purchased in the country of export destiny which complicates this substance flow analysis.

emission reductions are however difficult to capture. Indicative cost figures will be derived below:

To extend the recovery and recycling of $SF_6$ to smaller utilities and large individual factories (chemical or steel plants) with own GIS through the purchase of recycling equipment is the key abatement option (S2.1) considered here. It is assumed that the purchase of 300 pieces of recycling equipment at a cost of €33,000 each (including training) would reduce European emissions by 25%. This would lead to a total investment of €10m. Operating costs for the use of this equipment are basically labour costs minus the value of recovered $SF_6$. Here a net cost of €10,000 / yr per piece of equipment is used which adds up to €3m / yr for Europe.

**Table 16 Banked amounts of $SF_6$ in GIS, leakage rates and deduced emissions in 1995 based on results from a UNIPEDE survey presented by Neumann [1999][19]. Values for the Netherlands and Belgium have been estimated based on a personal communication by C. Neumann.**

| | $SF_6$ bank [t] | Effective loss rate [% / yr] | Emission due to leakage, repair and maintenance [t / yr] |
|---|---|---|---|
| Austria | 102 | 0.8 | 0.8 |
| Belgium | 34 | ~0.8 | 0.3 |
| Denmark | 7 | 3.5 | 0.2 |
| Finland | 34 | 1.5 | 0.5 |
| France | 784 | 0.8 | 6.3 |
| Germany | 989 | 0.8 | 7.9 |
| Greece | ~0 | (-) | ~0.0 |
| Great Britain | 477 | 5.0 | 23.9 |
| Ireland | 34 | 1.5 | 0.5 |
| Italy | 341 | 0.5 | 1.7 |
| Luxembourg | ~0 | (-) | ~0.0 |
| Netherlands | 171 | ~0.8 | 1.4 |
| Portugal | ~0 | (-) | ~0.0 |
| Spain | 102 | 1.2 | 1.2 |
| Sweden | ~0 | (-) | ~0.0 |
| **EU-15** | **3,410** | **(1.3)** | **44.7** |

**Baseline scenario:** It is assumed that emissions will remain constant in 2010 relative to 1995 levels. This implies that leakage emissions from new equipment will be

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[19] One reviewer cautioned that this survey may have been based on inaccurate or incomplete data for some countries, like e.g. the UK.

significantly lower than presently and that specific maintenance emissions will also decrease while the amount of banked $SF_6$ continues to grow.

### *3.2.3 Other sources*

**Background and base year emissions:** The relevance of other uses of $SF_6$ within the European countries is difficult to estimate. In Germany the filling of car tires with $SF_6$ to reduce leakage and the use of $SF_6$ in sound insulating double glazing have absorbed 100 and 180 tons in 1990 and 130 and 275 tons in 1995 [Öko-Recherche, 1996]. They thus have approximately the same relevance as the electrical sector. A study for Great Britain indicates that both applications are apparently minor there [March, 1999]. The emissions of $SF_6$ from the soles of certain sport shoes and tennis balls are estimated to be minor in Germany [Öko-Recherche, 1996]. The same study also concludes that emissions from scientific accelerators (van-de-Graff), in which $SF_6$ is used as insulating gas, are small in Germany which is in agreement with global estimates by Harnisch and Prinn [1999]. To derive emission estimates for the European countries it is assumed that German emissions (about 120 and 220 tons / yr, in 1990 and 1995 respectively) were responsible for 50% of European emission. The other 50% were distributed over the other 14 countries according to their GDP.

**Key abatement options:** No specific abatement options were considered for this field. The use of $SF_6$ in some of these application will soon be abandoned, e.g. in car tyres or sport shoes. The use of $SF_6$ in sound insulating windows is also rapidly declining due to public pressure. The level of emissions will nevertheless remain quite significant beyond 2010 because effective abatement options for the recovery of $SF_6$ from windows at demolition sites are unlikely to be developed.

**Baseline scenario:** A stabilisation of this emission category on the 1995 level is assumed for 2010. Mainly emissions from the decommissioning of sound insulation windows are responsible for the these emissions [Öko-Recherche, 1996]. Emissions are distributed as described above.

### 3.2.4 Manufacturing and distribution losses losses

**Background, base year emissions and baseline scenario:** As for the HFCs a constant loss rate of 2% $SF_6$ is assumed associated with its manufacturing, packaging and distribution. Total emissions are broken up according to countries' GDP. Our estimates thus do not reflect national regulations or the particular production sites. It is assumed that annual sales of $SF_6$ were 2,100 tons in 1990, 2,600 tons in 1995 and will be 2,600 tons in 2010 (based on estimates in Maiss and Brenninkmeijer [1998]). If manufacturing and distribution losses were much larger for $SF_6$ than for HFCs this could at least partly explain the discrepancy between sales data, derived emission estimates and observed atmospheric accumulation rates.

**Abatement options:** No abatement options for this source were analysed in this study. More reliable quantitative information on this source of emissions and their abatement are clearly needed.

## 3.3 Perfluorocarbons

The groups of perfluorocarbons (PFCs) comprise a large number of different subtances. Emissions of perfluorocarbons are generally only loosely tied to underlying economic activities. PFCs include a large number of potentially commercially relevant compounds. Production and sales date are generally not available and atmospheric observations that monitor global emissions are still in a pioneering state [e.g. Harnisch et al., 1996; Harnisch et al., 1999].

### 3.3.1 Primary aluminium production

**Background:** 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. 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 (Table 18) 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 last is clearly the most radical option which has been quite relevant for some countries of the European Union in recent years as can be seen in Table 17. Closures were always carried out for economic reasons. It is not anticipated that the use of inert anode technologies will contribute to near term emission reductions in Europe.

**Table 17 List of individual aluminium smelters, production technology and estimated production in 1990, 1995 and 1998 [personal communication - European Aluminium Association; Öko-Recherche, 1996].**

| | | Technology | | | Production [kt / yr] | | |
|---|---|---|---|---|---|---|---|
| **Country** | **Site** | **1990** | **1995** | **1998** | **1990** | **1995** | **1998** |
| Austria | Ranshofen | HSS | closed | Closed | 80 | 0 | 0 |
| Austria | Lend | PFPB | closed | Closed | 10 | 0 | 0 |
| France | Auzat | SWPB | SWPB | SWPB | 45 | 45 | 45 |
| France | Graveline | constr. | PFPB | PFPB | 0 | 215 | 220 |
| France | Lannemezan | SWPB | SWPB | SWPB | 45 | 45 | 45 |
| France | St. Jean | PFPB | PFPB | PFPB | 125 | 125 | 125 |
| France | Venthon | PFPB | closed | Closed | 30 | 0 | 0 |
| France | Nougeres | VSS | closed | Closed | 75 | 0 | 0 |
| France | Riouperoux | SWPB | closed | Closed | 10 | 0 | 0 |
| Germany | Hamburg | CWPB | CWPB | PFPB | 110 | 120 | 120 |
| Germany | Voerde | PFPB | PFPB | PFPB | 78 | 80 | 82 |
| Germany | Essen | PFPB | PFPB | PFPB | 136 | 95 | 126 |
| Germany | Stade | SWPB | SWPB | SWPB | 70 | 70 | 70 |
| Germany | Norf | CWPB | CWPB | PFPB | 210 | 210 | 210 |
| Germany | Töging | PFPB | PFPB | Closed | 29 | 29 | 0 |
| Germany | Töging | SWPB | SWPB | Closed | 61 | 61 | 0 |
| Germany | Rheinfelden | PFPB | closed | Closed | 42 | 0 | 0 |
| Germany | Lauta | HSS | closed | Closed | 15 | 0 | 0 |
| Germany | Bitterfeld | SWPB | closed | Closed | 18 | 0 | 0 |
| Greece | St. Nicolas | PFPB | PFPB | PFPB | 150 | 131 | 150 |
| Italy | Fusina | PFPB | PFPB | PFPB | 38 | 40 | 43 |
| Italy | Porto Vesme | SWPB | PFPB | PFPB | 127 | 136 | 145 |
| Italy | Fusina | SWPB | closed | Closed | 30 | 0 | 0 |
| Netherlands | Delfzijl | SWPB | SWPB | PFPB | 98 | 81 | 98 |
| Netherlands | Vlissingen | SWPB | SWPB | SWPB | 175 | 135 | 175 |
| Spain | La Coruna | VSS | VSS | VSS | 82 | 80 | 82 |
| Spain | San Ciprian | SWPB | SWPB | PF/SWPB | 190 | 197 | 197 |
| Spain | Aviles | VSS | VSS | VSS | 82 | 84 | 82 |
| Sweden | Sundsvall | VSS | VSS | VSS | 75 | 75 | 75 |
| Sweden | Sundsvall | PFPB | PFPB | PFPB | 25 | 25 | 25 |
| UK | Holyhead | PFPB | PFPB | PFPB | 125 | 134 | 135 |
| UK | Kinlochleven | VSS | VSS | VSS | 11 | 11 | 11 |
| UK | Fort William | PFPB | PFPB | PFPB | 38 | 38 | 38 |
| UK | Lynemouth | SWPB | PFPB | PFPB | 130 | 70 | 70 |
| **EU-15** | | | | | **2,565** | **2,332** | **2,369** |

**Table 18 Production technology and applied emission factors [IPCC/OECD/IEA, 1999b (CWPB, SWPB, VSS, HSS); Harnisch et al., 1999 (PFPB)].**

| Technolgy | | Emission factor [kg $CF_4$ eq. / t(Al)] |
|---|---|---|
| Pointfeeder Prebake | PFPB | 0.06 |
| Center Worked Prebake | CWPB | 0.4 |
| Side Worked Prebake | SWPB | 1.9 |
| Vertical Stud Söderberg | VSS | 0.7 |
| Horizontal Stud Söderberg | HSS | 0.7 |

**Base year emissions**

Emissions are calculated using default emission factors based on recommendations by IPCC/OECD/IEA [1999] (Table 18). Emission estimates are reported in Table 19. It should be kept in mind that emission estimates based on fixed emission factors can only be first approximations and need to be complemented with smelter specific data on the occurrence of anode effects. The European Aluminium Association has collected and reported such data but not yet published on a smelter-by-smelter basis as required for this assessment.

**Table 19 Estimated emissions of $CF_4$ and $C_2F_6$ as tons of $CF_4$-equivalents. Values without parentheses are based on default factors (Table 18) and the mix of technology for each country (Table 17). Estimates reported to the European Aluminium Association (personal communication Eirik Nordheim) are listed in parentheses.**

| | 1990 | 1995 | 1998 / 2010 |
|---|---|---|---|
| Austria | 55 (36) | 0 (0) | 0 (0) |
| France | 251 (343) | 191 (94) | 192 (125) |
| Germany | 422 (351) | 375 (201) | 165 (172) |
| Greece | 9 (55) | 8 (12) | 9 (10) |
| Italy | 301 (139) | 11 (50) | 11 (13) |
| Netherlands | 519 (341) | 410 (322) | 338 (258) |
| Spain | 474 (262) | 487 (247) | 306 (128) |
| Sweden | 53 (69) | 53 (51) | 53 (38) |
| United Kingdom | 264 (306) | 4 (43) | 4 (29) |
| **EU-15** | **2,347 (1,902)** | **1,557 (1,018)** | **1,096 (774)** |

**Key abatement options:** It is assumed that after 1998 the abatement of PFCs emissions will involve retrofitting and conversion of existing smelters [Harnisch et al., 1998]. The investment cost estimates from Harnisch et al. [1998] were modified for this analysis:

investment costs were inflated from 1985-US-dollars to 1999 Euros and emission factors were updated to be consistent with those recommended by IPCC/OECD/IEA [1999]. It is assumed that 100% and 50% of the older European smelter capacity are suitable for conversion and retrofitting, respectively. To take into account economic gains from higher energy efficiency and reduced labour costs from retrofitting and conversion respective default cost reductions of €20 and €75 per ton Al were applied for SWPB. According to information provided by the European Aluminium Association no significant gains in operating costs can be expected from conversion from VSS to PFPB. For retrofitting of VSS it is assumed that cost are reduced by €10 per ton aluminium. Results are given in Table 20. These savings greatly depend on specific conditions at each smelter.

**Table 20 Specific costs for conversion and retrofitting of smelter capacity. Investment costs (1999) after Harnisch et al. [1998] (inflated by a factor 1.46). Changes of operating costs are own indicative estimates. Values in parentheses were provided by Eirik Nordheim (EN) from the EAA as personal communication.**

| Abatement measure | Code | Total investment costs [€ / t(Al) / yr] | Change of operation costs [€ / t(Al) / yr] |
|---|---|---|---|
| SWPB to PFPB conversion | P1.1.1 | 530 (EN: 200-1000) | - 75 (EN: -40) |
| SWPB retrofitting | P1.1.2 | 60 (EN: not relevant for EU) | - 20 (EN: not relevant in EU) |
| VSS to PFPB conversion | P1.2.1 | 2200 (EN: 2000-4000) | 0 (EN: -50) |
| VSS retrofitting | P1.2.2 | 100 (EN: 100-250) | - 10 (EN: -10) |

**Baseline scenario:** It is not expected that new smelters will be constructed in western Europe during this decade. More likely older smelters will be de-commissioned. For the baseline scenario it is assumed that production numbers and emissions remain constant from 1998 until the end of the first commitment period of the Kyoto Protocol.

### 3.3.2 Semiconductor manufacture

**Background and base year emissions:** The use of PFCs, HFCs, $SF_6$ and $NF_3$ in the production of semiconductors is common to CVD (chemical vapour deposition) chamber cleaning (roughly 70%) and dry etching procedures (roughly 30%) associated with extremely small structures, i.e. ≤1 µm. By means of plasma discharge the source molecules are decomposed and thus release fluorine into the reactor which volatises silicon or silicon dioxide. Commonly only part of the applied fluorinated gases is destroyed in the process. Part is released unaffected while new perfluoro compounds may also form from fragments of the original chemicals.

The output of the semiconductor industry has grown by a mean rate of +17% between 1960 and 2000. In addition to this impressive expansion, PFC use in the semiconductor productions has grown even more rapidly during the 1990's following the industry trend towards smaller and more complex structures. Typical emissions vary greatly from process to process and site to site depending on the complexity of the chips and the specific technologies applied. Aggregate European PFC consumption and emission data for 1995 -1998 were provided by EECA (European Electronic Component Manufacturers Association). National data are currently virtually unavailable.

To arrive at national proxy data on the production of these specific semiconductors, it was assumed that sales of active electronic components roughly resemble production. Sales data were obtained from EECA. For countries that are not members of EECA the members' mean ratio of active component sales over GDP was used instead to derive estimates from their GDP. PFC emissions in Europe were then distributed according to real and proxy sales of active electronic components (Table 21). Emissions in 1990 are arbitrarily set to 1/5 of estimated 1995 values.

**Key abatement options:** Intensive research is currently under way to reduce PFC emissions associated with the production of semiconductors. New options are thus likely to evolve during this decade. Below only three technologically proven options with known economics are included. Table 22 gives an overview of the respective potential.

CVD Chamber Clean:

For future tools a switch from $C_2F_6$ to $NF_3$ (P2.1) offers considerable potential to reduce emissions from this source in terms of $CO_2$ equivalents due to a significantly higher utilisation efficiency within the chamber. This way reductions of up to 99% of equivalent $CO_2$ emissions can be achieved along with increased throughput of the equipment. Though today not feasible for old equipment this route can be taken for new equipment. This study estimates that in 2010 almost 90% of CVD systems will have been installed in 2000 or later. For new equipment based on $NF_3$ chemistry additional investment costs are in order of €70,000 per chamber. In this study an average value of 200 kg / yr of $C_2F_6$ per chamber is used. The exhaust gas contains $NF_3$, $F_2$, $SiF_4$ and HF all of which are toxic and should not be released into the environment. The costs for the disposal or treatment of occurring dilute hydrofluoric acid from a wet scrubber system thus need to be taken into account: a mean value of €33,000 / yr is used based on information provided by EECA.

**Table 21 Semiconductor industry: estimated emissions in 1990, 1995 and the baseline for 2010. The European semiconductor manufacturers have committed themselves to a 10% reduction relative to the 1995 base year.**

| | Estimated emissions [tons PFC / yr] | | |
|---|---|---|---|
| | **1990** | **1995** | **2010** |
| Austria | 1 | 10 | 60 |
| Belgium | 1 | 0 | 40 |
| Denmark | 1 | 10 | 50 |
| Finland | 1 | 0 | 30 |
| France | 10 | 50 | 400 |
| Germany | 17 | 80 | 680 |
| Greece | 1 | 0 | 30 |
| Great Britain | 16 | 80 | 670 |
| Ireland | 0 | 0 | 20 |
| Italy | 4 | 20 | 180 |
| Luxembourg | 0 | 0 | 0 |
| Netherlands[20] | 1 | 10 | 60 |
| Portugal | 1 | 0 | 30 |
| Spain | 2 | 10 | 70 |
| Sweden | 3 | 20 | 140 |
| **EU-15** | **60** | **300** | **2,430** |

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[20] One reviewer commented that the proxy method certainly underestimates Dutch emissions of PFCs from the semiconductor sector.

Etching:

The gas used in the etching step critically influences product yield and quality. Modifications to existing processes thus require a lengthy and expensive re-qualification procedure. It is expected that for newly installed equipment it will become a viable option to switch to alternative compounds (P2.2) (e.g. $C_4F_8$ and $C_5F_{10}$) with associated emission reduction of 30% relative to the $C_2F_6$ baseline is viable for etching processes in newly installed equipment and here assumed to be available at no costs. Again almost 90% of etch processes in 2010 will run on equipment from 2000 or younger.

Roughly 90% of remaining 2010 emissions from etching in equipment installed after 1999 could be abated by post-combustion (P2.3). Investment costs for one system abating 200kg of $C_2F_6$ per year are estimated to be around €70,000. Operation costs are estimated to be roughly €30,000 / yr for energy and €33,000 / yr for the disposal or treatment of additional dilute hydrofluoric acid (based on information provided by EECA). If the equipment is not burning idle for a large part of its time, the effect of $CO_2$ emissions from the combustion process (about 30 tons / yr) is relatively small compared to the abated amount of $CO_2$ equivalents of abated PFCs.

**Table 22 Projected emission in 2010 and associated reduction options. The year 1999 marks the limit between "old" and "new" equipment.**

| Source | Projected PFC emissions in 2010 | Reduction potential | Technology + Code |
|---|---|---|---|
| **Cleaning - old CVD** | **180 tons / yr<br>= 1.2 MT $CO_2$ eq.** | **?** | **Alternative chemistry, e.g. $C_3F_8$** |
| **Cleaning - new CVD** | **1500 tons / yr<br>= 9.8 MT $CO_2$ eq.** | **99 %** | **$NF_3$ technology (P2.1)** |
| **Etching in old equipment** | **80 tons / yr<br>= 0.6 MT $CO_2$ eq.** | **0%** | **Currently not available** |
| **Etching in new equipment** | **650 tons / yr<br>= 4.2 MT $CO_2$ eq.** | **30 %<br>60 %** | **Alternative chemistry (P2.2)<br>Thermal oxidation (P2.3)** |
| **European Industry Total** | **2,400 tons / yr<br>= 16 MT $CO_2$ eq.** | **(86%)** | **P2.1 + P2.2 + P2.3** |
| **WSC-Target** | **1.8 MT $CO_2$ eq.** | **Requires a reduction of 89% from the baseline in 2010** | |

The largest technical and economic problems in reducing PFC emissions exist for older equipment existing already in 1999 (Table 22). In this study it is assumed that 50% of this old equipment will be decommissioned in 2010. Generally it should be kept in mind, that no single measure can be applied to reduce the PFC emissions across the semiconductor industry. Several factors like the variety or tools and processes, space constraints in existing production sites, product mix, and technology affect the applicability of PFC emission reduction technologies. Manufacturers wish to maintain flexibility to determine the best emission reduction strategy for each company. The cost estimates of this study does not include benefits from increased throughput which could partly offset abatement calculated costs.

**Baseline scenario:** It is assumed that between 1995 to 2010 the European semiconductor industry continues its growth path at rate of 15% / yr leading to an increase of projected emissions by a 740%. The World Semiconductor Council, which comprises most large semiconductor manufacturers, has agreed in a voluntary agreement to reduce its absolute global emissions of PFCs in 2010 by 10% relative to the 1995 baseline. This agreement was not included into the baseline projection of this study as considerable costs will occur directly connected to mitigate greenhouse gas emissions in order to meet this reduction target.

### 3.3.3 Other sources

**Background and base year emissions and baseline scenario:** In 1995 there was some use of PFCs as solvents in electronics applications and as minor compounds in foam blowing agents and refrigerant mixtures. Manufacturing and distribution losses occur just as described above for HFCs and $SF_6$. New uses are evolving in the medical field and in cosmetics. In military first aid PFCs are used as artificial blood. Also certain military radar-systems sometimes require a filling with PFCs. Atmospheric observations suggest that $c\text{-}C_4F_8$ is accumulating in the atmosphere at a rate of about 1,000-2,000 tons / yr [Harnisch, 1999]. The source has not yet been identified. The thermal combustion of fluoropolymers is a possible candidate along with submarine refrigeration applications. The quantification of these miscellaneous emission sources requires further investigation. It would be misleading to assume that these PFC-emissions are non significant for the EU. Based on the estimates by Harnisch et al. [1998] we assume that gross emissions of 400 and 500 tons / yr occurred in 1990 and 1995. Future emissions in 2010 are projected to remain at 500 tons / yr. These emissions are assigned to countries according to GDP. Further information on specific processes and the national situations is clearly needed.

**Abatement options:** No abatement options for this group of sources were identified. More reliable quantitative information on the source of these emissions and their abatement are clearly needed.

# 4 Results

## *4.1 Aggregated emissions 1990, 1995 and baseline until 2010*

Emission estimates derived above are compiled in this paragraph and presented in a graphical format on aggregate European level in Figure 1, Figure 2 and Figure 3. Tabulated emissions of HFCs can be found in Table 23, Table 24 and Table 25 for the years 1990, 1995 and 2010. Respective values for PFCs and $SF_6$ are given in Table 26, Table 27 and Table 28. Sums for the three groups are given in Table 29. The total aggregates for HFCs, PFCs and $SF_6$ are listed in Table 30.

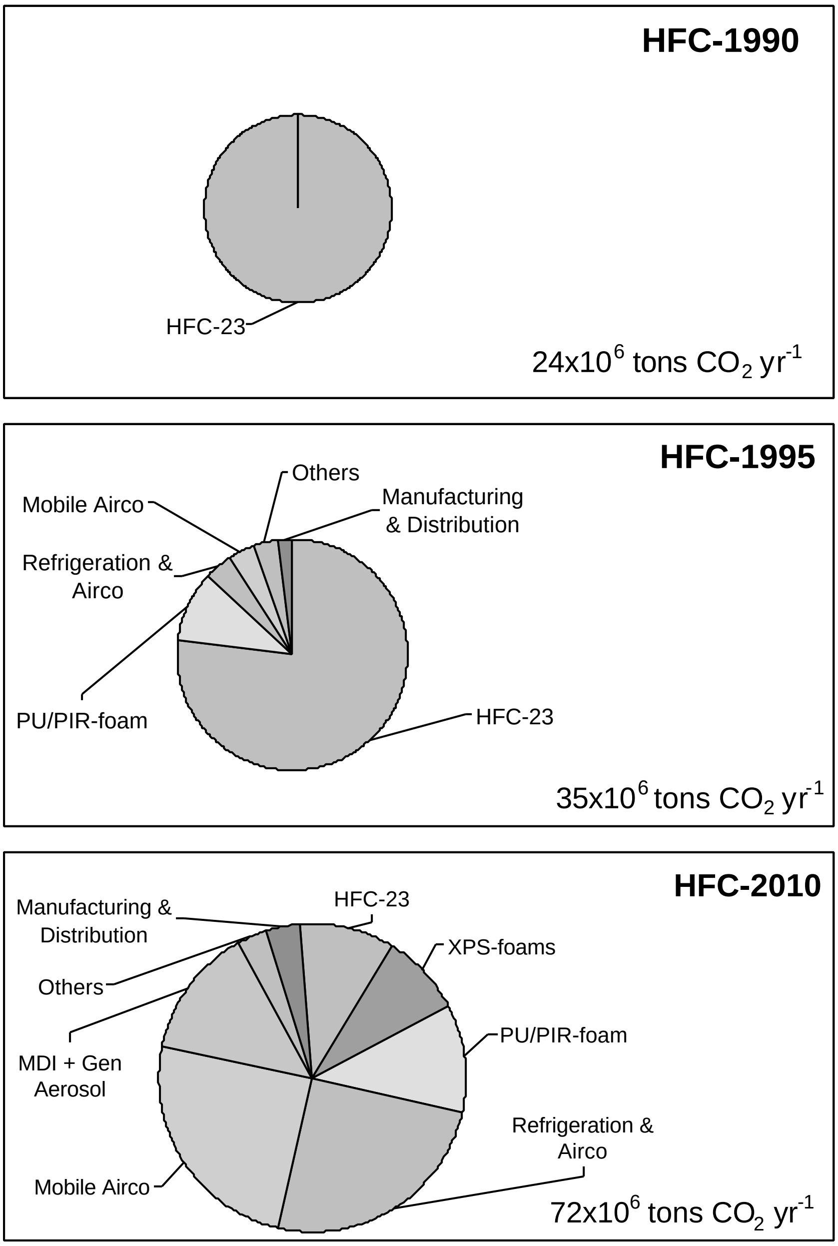

**Figure 1 Aggregate European HFC Emissions in 1990, 1995 and 2010.**

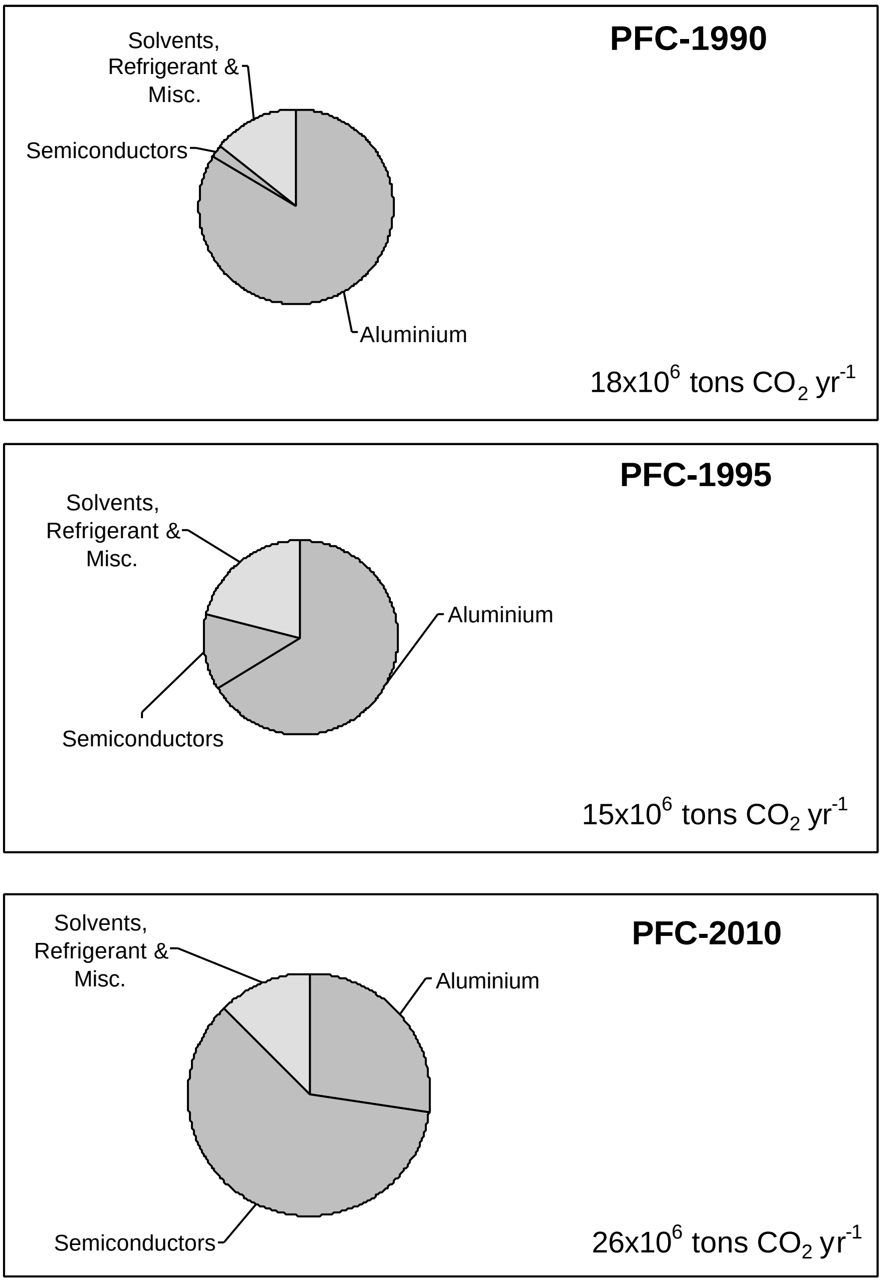

**Figure 2 Aggregate European PFC Emissions in 1990, 1995 and 2010.**

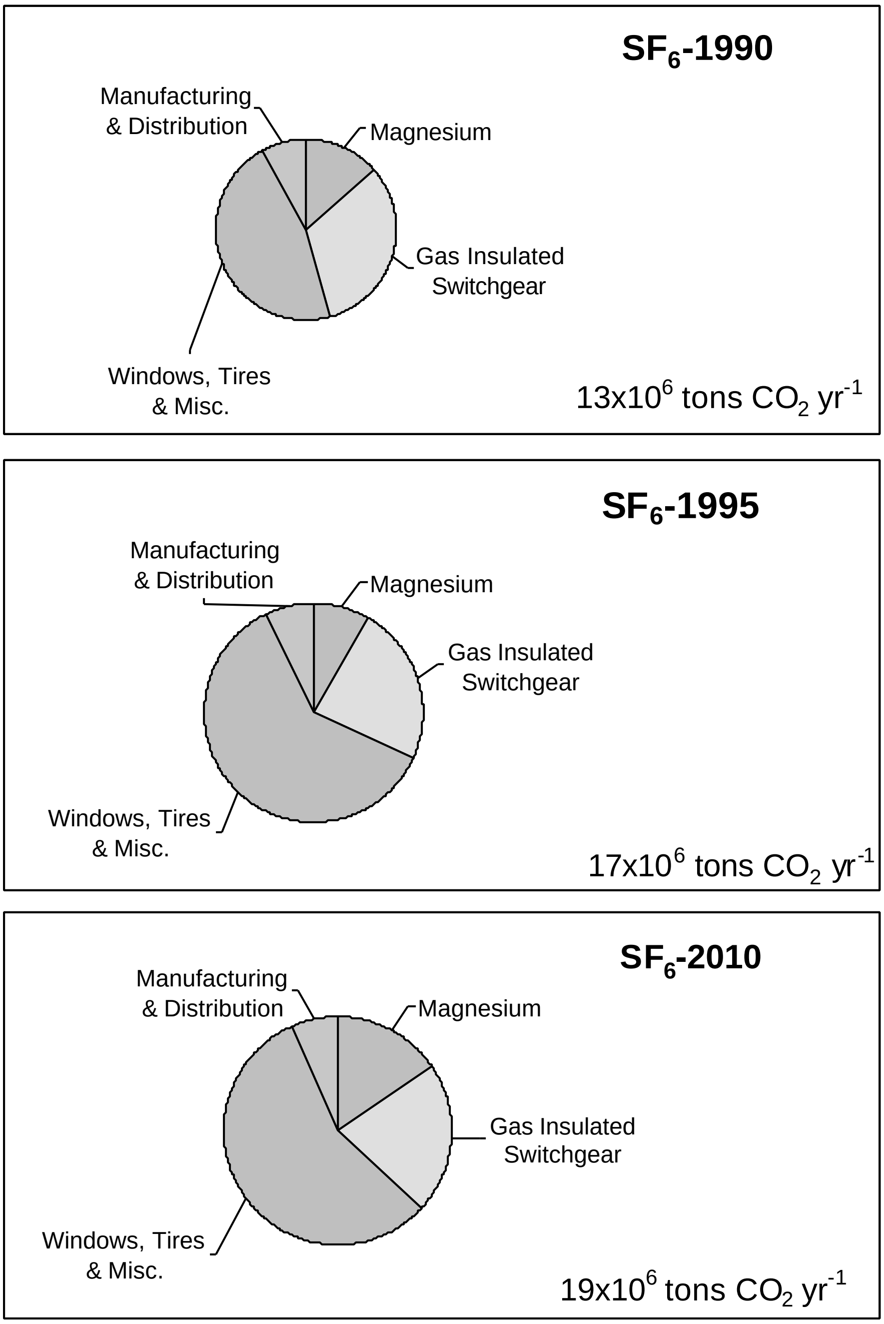

**Figure 3 Aggregate European $SF_6$ Emissions in 1990, 1995 and 2010.**

**Table 23 Estimated emissions of HFCs from different applications[21] in 1990 [Million CO$_2$ equivalents / yr].**

| | HFC-23 | XPS | PU/PIR | Ref. & SAC | MAC | MDI + GAero | Others | Man-Distr | Total |
|---|---|---|---|---|---|---|---|---|---|
| Austria | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Belgium | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Denmark | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Finland | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| France | 2.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.8 |
| Germany | 5.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.4 |
| Greece | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 |
| Great Britain | 4.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.8 |
| Ireland | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Italy | 3.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.1 |
| Luxembourg | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Netherlands | 3.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.9 |
| Portugal | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Spain | 3.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.1 |
| Sweden | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **EU-15** | **23.6** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **23.6** |

**Table 24 Estimated emissions of HFCs from different applications in 1995 [Million tons CO$_2$ equivalents / yr].**

| | HFC-23 | XPS | PU/PIR | Ref. & SAC | MAC | MDI + GAero | Others | Man-Distr | Total |
|---|---|---|---|---|---|---|---|---|---|
| Austria | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 |
| Belgium | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 |
| Denmark | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| Finland | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| France | 3.6 | 0.0 | 0.5 | 0.2 | 0.2 | 0.0 | 0.2 | 0.1 | 4.9 |
| Germany | 3.4 | 0.0 | 1.4 | 0.4 | 0.3 | 0.0 | 0.4 | 0.2 | 6.0 |
| Greece | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 |
| Great Britain | 6.1 | 0.0 | 0.4 | 0.2 | 0.2 | 0.0 | 0.2 | 0.1 | 7.1 |
| Ireland | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| Italy | 4.0 | 0.0 | 0.4 | 0.2 | 0.2 | 0.0 | 0.2 | 0.1 | 5.0 |
| Luxembourg | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Netherlands | 4.9 | 0.0 | 0.1 | 0.1 | 0.0 | 0.0 | 0.1 | 0.0 | 5.2 |
| Portugal | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| Spain | 4.0 | 0.0 | 0.2 | 0.1 | 0.1 | 0.0 | 0.1 | 0.0 | 4.5 |
| Sweden | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 |
| **EU-15** | **26.5** | **0.0** | **3.4** | **1.3** | **1.2** | **0.0** | **1.3** | **0.7** | **34.5** |

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[21] The following abbreviations are used in these tables: ManDistr=manufacturing and distribution, HFC-23=by-product of HCFC-22 production, XPS=Extruded polystyrene, PU/PIR=Emissions associated with the polyurethane and similar foams, Ref & SAC=refrigeration and stationary air conditioning, MAC = mobile air conditioning, MDI + GAero=Metered Dose Inhalors and General Aerosols.

**Table 25 Projected emissions of HFCs from different applications in 2010 [Million tons $CO_2$ equivalents / yr].**

| | **HFC-23** | **XPS** | **PU/PIR** | **Ref. & SAC** | **MAC** | **MDI + GAero** | **Others** | **Man-Distr** | **Total** |
|---|---|---|---|---|---|---|---|---|---|
| Austria | 0.0 | 0.5 | 0.1 | 0.5 | 0.4 | 0.2 | 0.1 | 0.1 | **1.8** |
| Belgium | 0.0 | 0.2 | 0.3 | 0.6 | 0.6 | 0.3 | 0.1 | 0.1 | **2.1** |
| Denmark | 0.0 | 0.0 | 0.1 | 0.4 | 0.2 | 0.2 | 0.0 | 0.1 | **1.0** |
| Finland | 0.0 | 0.0 | 0.0 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | **0.6** |
| France | 0.2 | 0.8 | 1.3 | 3.3 | 2.8 | 1.7 | 0.4 | 0.5 | **11.0** |
| Germany | 0.3 | 2.2 | 2.8 | 5.0 | 4.6 | 2.6 | 0.6 | 0.7 | **18.9** |
| Greece | 0.6 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.0 | 0.0 | **1.5** |
| Great Britain | 1.6 | 0.5 | 0.7 | 2.5 | 2.9 | 1.4 | 0.3 | 0.4 | **10.2** |
| Ireland | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.1 | 0.0 | 0.0 | **0.5** |
| Italy | 0.2 | 0.8 | 1.2 | 2.6 | 2.7 | 1.4 | 0.3 | 0.4 | **9.7** |
| Luxembourg | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **0.1** |
| Netherlands | 0.2 | 0.3 | 0.4 | 0.8 | 0.7 | 0.4 | 0.1 | 0.1 | **3.2** |
| Portugal | 0.0 | 0.1 | 0.2 | 0.2 | 0.4 | 0.2 | 0.0 | 0.0 | **1.1** |
| Spain | 4.0 | 0.3 | 0.7 | 1.3 | 1.5 | 0.8 | 0.2 | 0.2 | **8.9** |
| Sweden | 0.0 | 0.4 | 0.1 | 0.5 | 0.3 | 0.3 | 0.1 | 0.1 | **1.7** |
| **EU-15** | **7.2** | **6.3** | **8.1** | **18.2** | **17.7** | **9.8** | **2.2** | **2.6** | **72.2** |

**Table 26 Estimated emissions of $SF_6$ and PFCs from different applications[22] in 1990 [Million tons $CO_2$ equivalents / yr].**

| | **Mg $SF_6$** | **Elec $SF_6$** | **Others $SF_6$** | **MfcDst $SF_6$** | **Alu PFC** | **Semi PFC** | **Others PFC** | **Total** |
|---|---|---|---|---|---|---|---|---|
| Austria | 0.0 | 0.0 | 0.1 | 0.0 | 0.4 | 0.0 | 0.1 | **0.6** |
| Belgium | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | **0.2** |
| Denmark | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | **0.2** |
| Finland | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **0.1** |
| France | 0.7 | 1.2 | 0.7 | 0.2 | 1.6 | 0.1 | 0.5 | **5.0** |
| Germany | 0.3 | 1.2 | 2.9 | 0.3 | 2.7 | 0.1 | 0.7 | **8.2** |
| Greece | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | **0.1** |
| Great Britain | 0.1 | 0.9 | 0.5 | 0.1 | 1.7 | 0.1 | 0.4 | **3.9** |
| Ireland | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **0.1** |
| Italy | 0.4 | 0.4 | 0.6 | 0.1 | 2.0 | 0.0 | 0.4 | **3.8** |
| Luxembourg | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **0.0** |
| Netherlands | 0.0 | 0.2 | 0.2 | 0.0 | 3.4 | 0.0 | 0.1 | **3.9** |
| Portugal | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **0.1** |
| Spain | 0.1 | 0.1 | 0.3 | 0.1 | 3.1 | 0.0 | 0.2 | **3.8** |
| Sweden | 0.0 | 0.1 | 0.1 | 0.0 | 0.3 | 0.0 | 0.1 | **0.7** |
| **EU-15** | **1.7** | **4.0** | **5.7** | **1.0** | **15.3** | **0.4** | **2.6** | **30.7** |

---

[22] The following abbreviations are used in these tables: Mg=magnesium casting, Elec=Electrical Switchgear (GIS), Others $SF_6$=Mainly car tires and sound insulating windows, MfcDst=manufacturing and distribution losses, Alu=primary aluminium production, Semi=semiconductor production.

**Table 27 Estimated emissions of $SF_6$ and PFCs from different applications in 1995 [Million tons $CO_2$ equivalents / yr].**

| | **Mg $SF_6$** | **Elec $SF_6$** | **Others $SF_6$** | **MfcDst $SF_6$** | **Alu PFC** | **Semi PFC** | **Others PFC** | **Total** |
|---|---|---|---|---|---|---|---|---|
| Austria | 0.1 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.1 | **0.4** |
| Belgium | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.1 | **0.4** |
| Denmark | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | **0.3** |
| Finland | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | **0.2** |
| France | 0.7 | 1.2 | 1.3 | 0.2 | 1.2 | 0.3 | 0.6 | **5.6** |
| Germany | 0.2 | 1.2 | 5.3 | 0.3 | 2.4 | 0.5 | 0.9 | **10.9** |
| Greece | 0.0 | 0.0 | 0.1 | 0.0 | 0.1 | 0.0 | 0.0 | **0.2** |
| Great Britain | 0.2 | 0.9 | 1.0 | 0.2 | 0.1 | 0.5 | 0.4 | **3.3** |
| Ireland | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | **0.1** |
| Italy | 0.1 | 0.4 | 1.0 | 0.2 | 0.1 | 0.1 | 0.5 | **2.4** |
| Luxembourg | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **0.0** |
| Netherlands | 0.0 | 0.2 | 0.3 | 0.1 | 2.7 | 0.0 | 0.1 | **3.4** |
| Portugal | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | **0.2** |
| Spain | 0.1 | 0.1 | 0.5 | 0.1 | 3.2 | 0.1 | 0.2 | **4.2** |
| Sweden | 0.1 | 0.1 | 0.2 | 0.0 | 0.3 | 0.1 | 0.1 | **0.9** |
| **EU-15** | **1.5** | **4.0** | **10.5** | **1.2** | **10.1** | **1.9** | **3.3** | **32.6** |

**Table 28 Projected emissions of $SF_6$ and PFCs from different applications in 2010 [Million tons $CO_2$ equivalents / yr].**

| | **Mg $SF_6$** | **Elec $SF_6$** | **Others $SF_6$** | **MfcDst $SF_6$** | **Alu PFC** | **Semi PFC** | **Others PFC** | **Total** |
|---|---|---|---|---|---|---|---|---|
| Austria | 0.2 | 0.0 | 0.2 | 0.0 | 0.0 | 0.4 | 0.1 | **0.9** |
| Belgium | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.2 | 0.1 | **0.6** |
| Denmark | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.3 | 0.1 | **0.5** |
| Finland | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.2 | 0.0 | **0.3** |
| France | 0.8 | 1.2 | 1.3 | 0.2 | 1.2 | 2.6 | 0.6 | **7.9** |
| Germany | 0.6 | 1.2 | 5.3 | 0.3 | 1.1 | 4.4 | 0.9 | **13.7** |
| Greece | 0.0 | 0.0 | 0.1 | 0.0 | 0.1 | 0.2 | 0.0 | **0.4** |
| Great Britain | 0.4 | 0.9 | 1.0 | 0.2 | 0.1 | 4.3 | 0.4 | **7.4** |
| Ireland | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.1 | 0.0 | **0.2** |
| Italy | 0.3 | 0.4 | 1.0 | 0.2 | 0.1 | 1.1 | 0.5 | **3.6** |
| Luxembourg | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **0.1** |
| Netherlands | 0.0 | 0.2 | 0.3 | 0.1 | 2.2 | 0.4 | 0.1 | **3.3** |
| Portugal | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.2 | 0.0 | **0.4** |
| Spain | 0.3 | 0.1 | 0.5 | 0.1 | 2.0 | 0.4 | 0.2 | **3.6** |
| Sweden | 0.3 | 0.1 | 0.2 | 0.0 | 0.3 | 0.9 | 0.1 | **1.9** |
| **EU-15** | **2.9** | **4.0** | **10.5** | **1.2** | **7.1** | **15.8** | **3.3** | **44.9** |

**Table 29 Evolution of HFC, PFC & $SF_6$ emissions in 1990, 1995 & 2010 [MT $CO_2$ eq.].**

| | HFC | | | PFC | | | $SF_6$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | **1990** | **1995** | **2010** | **1990** | **1995** | **2010** | **1990** | **1995** | **2010** |
| Austria | 0.0 | 0.2 | 1.8 | 0.4 | 0.1 | 0.4 | 0.1 | 0.3 | 0.4 |
| Belgium | 0.0 | 0.2 | 2.1 | 0.1 | 0.1 | 0.3 | 0.2 | 0.3 | 0.3 |
| Denmark | 0.0 | 0.1 | 1.0 | 0.1 | 0.1 | 0.4 | 0.1 | 0.2 | 0.2 |
| Finland | 0.0 | 0.1 | 0.6 | 0.0 | 0.1 | 0.2 | 0.1 | 0.1 | 0.1 |
| France | 2.8 | 4.9 | 11.0 | 2.2 | 2.2 | 4.4 | 2.8 | 3.5 | 3.5 |
| Germany | 5.4 | 6.0 | 18.9 | 3.6 | 3.9 | 6.4 | 4.7 | 7.0 | 7.4 |
| Greece | 0.5 | 0.7 | 1.5 | 0.1 | 0.1 | 0.3 | 0.1 | 0.1 | 0.1 |
| Great Britain | 4.8 | 7.1 | 10.2 | 2.2 | 1.1 | 4.9 | 1.7 | 2.2 | 2.4 |
| Ireland | 0.0 | 0.1 | 0.5 | 0.0 | 0.0 | 0.1 | 0.0 | 0.1 | 0.1 |
| Italy | 3.1 | 5.0 | 9.7 | 2.4 | 0.7 | 1.7 | 1.4 | 1.7 | 1.9 |
| Luxembourg | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Netherlands | 3.9 | 5.2 | 3.2 | 3.5 | 2.9 | 2.7 | 0.4 | 0.6 | 0.6 |
| Portugal | 0.0 | 0.1 | 1.1 | 0.0 | 0.1 | 0.2 | 0.1 | 0.1 | 0.1 |
| Spain | 3.1 | 4.5 | 8.9 | 3.3 | 3.4 | 2.7 | 0.5 | 0.8 | 1.0 |
| Sweden | 0.0 | 0.2 | 1.7 | 0.4 | 0.5 | 1.3 | 0.3 | 0.4 | 0.6 |
| **EU-15** | **23.6** | **34.5** | **72.2** | **18.2** | **15.3** | **26.2** | **12.5** | **17.2** | **18.7** |

**Table 30 Base year & projected total emissions of HFCs, PFCs & $SF_6$ [MT $CO_2$ eq].**

| | **1990** | **1995** | **2010** |
|---|---|---|---|
| Austria | 0.6 | 0.6 | 2.7 |
| Belgium | 0.2 | 0.6 | 2.7 |
| Denmark | 0.2 | 0.4 | 1.5 |
| Finland | 0.1 | 0.3 | 1.0 |
| France | 7.8 | 10.5 | 18.9 |
| Germany | 13.6 | 16.9 | 32.6 |
| Greece | 0.6 | 0.9 | 1.8 |
| Great Britain | 8.7 | 10.4 | 17.6 |
| Ireland | 0.1 | 0.2 | 0.7 |
| Italy | 6.9 | 7.4 | 13.3 |
| Luxembourg | 0.0 | 0.0 | 0.2 |
| Netherlands | 7.8 | 8.7 | 6.5 |
| Portugal | 0.1 | 0.3 | 1.5 |
| Spain | 6.9 | 8.7 | 12.6 |
| Sweden | 0.7 | 1.1 | 3.6 |
| **EU-15** | **54** | **67** | **117** |

## *4.2 Uncertainty of HFC-emission estimates*

The main growth of emissions is projected to occur through HFCs. Uncertainties of estimated base year emission and projected baseline (“business as usual”) thus deserve special exploration.

### 4.2.1 Comparison: Refrigeration & Air Conditioning on the National Level

As discussed in the respective section on refrigeration and air conditioning, significant simplifications had to be made to estimate fluid banks on the national level. Except for mobile air conditioning, the estimated French bank of refrigerants [Palandre et al., 1998] was used as the starting point for extrapolations to other countries.

Table 31 compares derived refrigerant banks for Germany. Apparently significant differences exist in certain sectors that require a more detailed comparison. March [1999] unfortunately did not report estimates of banked amounts of refrigerants in the UK for 2010. A comparison of emissions (Table 32) also reveal major differences.

Both comparisons indicate that the extrapolation from French data as used in this study may lead to an underestimation of refrigerant banks in commercial refrigeration and an overestimation of transport refrigeration. Regarding their effect on overall emission from the refrigeration sector both effects partly offset each other. Further research on this issue is clearly warranted.

**Table 31 Comparison of projected banked amounts of HFC in Germany in 2010 [tons].**

| | Öko-Recherche [1999] | This study |
|---|---|---|
| Commercial Refrigeration | 12,450 | 4,354 |
| Industrial Refrigeration & Large Scale Air Conditioning | 8,000 | 6,000 |
| Mobile Air Conditioning | 29,700 | 20,300 |
| Transport Refrigeration | 350 | 4,648 |

**Table 32 Comparison of projected emissions of HFCs in 2010 from major sub-sectors of refrigeration and air conditioning in the United Kingdom. Units are MT $CO_2$ eq.**

| | March [1999] | This study |
|---|---|---|
| Commercial Refrigeration | 1.6 | 0.6 |
| Mobile Air Conditioning | 1.3 | 2.9 |
| Industrial Refrigeration | 0.5 | 0.5 |
| Domestic Refrigeration | 0.2 | 0.1 |
| Air Conditioning DX | 0.4 | 0.3 |
| Air Conditioning Chillers | 0.1 | 0.2 |
| Transport Refrigeration | 0.1 | 0.9 |

### 4.2.2 Comparison on European Level

Estimates for Europe from this study and March [1998] are compared in Table 33 (1995 emissions) and Table 34 (2010 emissions). Estimated 1995 base year emissions by March [1998] are about 35% above our findings (if OCF and REF & SAC emissions are taken into account). Projected baseline emissions for 2010 from March [1998] are 10% below our findings (again, if missing OCF emissions are taken into account).

**Table 33 Comparison of European HFC emission estimates for 1995**

| | **This study [MT $CO_2$ eq.]** | **March [1998] [MT $CO_2$ eq.]** | **Comment** |
|---|---|---|---|
| HFC-23 | 27 | 35 | different assumptions on the existing abatement and higher emission factor by March [1998] |
| Foams | 3.4 | 0 | March [1998] did not include OCF |
| REF & SAC | 1.3 | 0 | March [1998] estimated that these emission were insignificant in 1995 |
| MAC | 1.2 | 4.3 | both studies use different emission factors for 1995 |
| Others | 2.0 | 1.4 | this study mainly based on March [1998] |
| **TOTAL** | **35** | **41** | |

The main difference between the 1995 estimates originates from the contribution of HFC-23 from HCFC-22 manufacture. While the March [1998] emission factor for this process - apparently about 3.5% - is 70% higher than ours (and the global industry average) European production numbers for HCFC-22 must have been about 30% below our data to arrive at the value of 35 MT $CO_2$ eq. The difference for 1995 emission values for mobile air conditioning requires further investigations but is very likely due to different assumptions of emission factors and the exact timing of the phase in of HFCs in this sector.

**Table 34 Comparison of projected European HFC emission in 2010 (baseline)**

| | **This study [MT $CO_2$ eq.]** | **March [1998] [MT $CO_2$ eq.]** | **Comment** |
|---|---|---|---|
| HFC-23 | 7 | 10 | |
| Foams | 14 | 14 | Different emission factors and Assumptions on HFC usage compensate |
| REF & SAC | 18 | 19 | Different emission factors and Assumptions on HFC usage compensate |
| MAC | 18 | 9 | Different leakage rate in 2010 |
| Others | 15 | 15 | this study is based on March [1998] |
| **TOTAL** | **72** | **66** | |

The rather good agreement between projected emission for 2010 maybe coincidental taking into account that for foams and the REF & SAC sectors both studies used significantly different emission factors. For these two sectors March [1998] estimated higher HFC-consumption values. At the same time significantly lower emission factors were applied by March [1998]. Both differences partly offset each other and thus lead to similar results as in our study. The difference for emission estimates from MAC basically origin from a lower emission leakage in 2010 (4% as compared to 10% in our study).

Uncertainties of base year emission estimates can probably be narrowed down to ± 10% if manufacturers provide HCFC-22 production data including feedstock use and provide validated emission factors for the production of HFC-23 in their plants. The emission projections for 2010 are much more uncertain than suggested by the reasonable agreement of numbers in Table 34. The three main sources of uncertainty are emission factors, economic activity data and the assumptions of the “business and usual” market penetration of a HFC solution. All three aspects still require considerable independent research to make reliable projections of future HFC emission levels.

## 4.3 Cost estimates

This paragraph reports the results of the abatement cost assessment. The emission reductions are calculated on an annual basis. All cost data of this report are calculated as

1999 Euros except for those in Table 36 which have been deflated to 1990 European prices by dividing by the EUROSTAT industrial producer price index of 1.15 to ensure consistency with the cost reporting of "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change". 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) with discount rates of 2%, 4% and 6% (see Table 36). The approach using annualised costs evaluates measures according to their long term suitability to mitigate global warming. The approach does not take into account that some measures are available too late to reach their full abatement potential during the first commitment period of the Kyoto Protocol. Mobile air conditioning systems based on $CO_2$ technology (phase-in possible starting in 2004) are a good example for this.

Table 35 and Table 36 list the evaluated measures in a technological order and least cost order, respectively. In Table 37 lists aggregated abatement costs for different sectors. The costs are calculated as weighted means of sub-sectors. This preliminary list of groups of low cost measures contains a selection of abatement options with proven technologies and robust cost information. Finally, Table 38 lists those processes for which no abatement options were included into this study due to the complexity of the particular sector (e.g. solvents) or because of unresolved non-monetary issues about the acceptability of non-HFC alternatives (e.g. MDIs). Further research is clearly needed for the solvent sector, the “other” $SF_6$ and PFC applications and the emissions associated with manufacturing and distribution.

**Table 35 Cost information (in 1999 prices) estimates for emission reduction options for the 2010 baseline (investment costs discounted with 4%) - systematic order**

| measure | code | abated emiss [MT $CO_2$ eq / yr] | Total invest costs [M€] | annual costs [M€ / yr] | abatemnt cost [€/ t $CO_2$ eq] |
|---|---|---|---|---|---|
| HFC-23: oxidation | H1.1 | 6.8 | 8 | 0.8 | 0.2 |
| Foam PU-appliances: pentane | H2.1.1 | 0.2 | 24 | 12 | 72 |
| Foam PU-continuous panels: pentane | H2.2.1 | 0.2 | 3 | 7 | 33 |
| Foam PU-flexibl. faced laminate: pentane | H2.3.1 | 0.8 | 10 | 18 | 24 |
| Foam PU-discontinuous panels: pentane | H2.4.1 | 0.7 | 35 | 18 | 32 |
| Foam PU-pipe in pipe: pentane | H2.5.1 | 0.1 | 3 | 0 | 3.1 |
| Foam PU-spray: water | H2.6.1 | 1.4 | 10 | 28 | 21 |
| Foam PU-one component: hydrocarbons | H2.7.1 | 3.5 | 16 | 0 | 0.4 |
| Foam PU-blocks: pentane | H2.8.1 | 0.9 | 105 | 18 | 31 |
| Foams XPS: carbon dioxide | H2.9.1 | 6.3 | 63 | 30 | 5.7 |
| Domestic refrigeration: hydrocarbons | H3.1.1 | 1.1 | 40 | 0 | 3.4 |
| Domestic refrigeration: recovery | H3.1.2 | 0.8 | 10 | 75 | 90 |
| Commercial refrig.: hydrocarbons a. NH3 | H3.2.1 | 4.3 | 1571 | 251 | 92 |
| Commercial refrigeration: leakage reduction | H3.2.2 | 1.7 | 157 | 79 | 54 |
| Industrial food refrig.: hydrocarbons a. NH3 | H3.3.1 | 2.4 | 442 | -33 | 2.7 |
| Industrial food refrig: leakage reduction | H3.3.2 | 1.0 | 44 | 55 | 62 |
| Industrial refrigeration: hydrocarbons a. NH3 | H3.4.1 | 1.4 | 256 | -19 | 2.7 |
| Industrial refrigeration: leakage reduction | H3.4.2 | 0.6 | 26 | 32 | 62 |
| Transport refrigeration: leak reduction | H3.5.1 | 2.8 | 84 | 84 | 33 |
| Stationary air conditioning DX: hydrocarbons | H3.6.1 | 1.4 | 437 | 122 | 114 |
| Stationary air conditioning DX: leak reduction | H3.6.2 | 0.6 | 35 | 22 | 44 |
| Stationary air conditioning chiller: HC &NH3 | H3.7.1 | 0.7 | 174 | 17 | 49 |
| Stationary air conditioning chiller: leak reduct. | H3.7.2 | 0.3 | 35 | 43 | 173 |
| Mobile air conditioning: carbon dioxide | H4.1 | 8.9 | 2500 | 0 | 25 |
| Mobile air conditioning: leakage red. | H4.2 | 6.6 | 500 | 0 | 6.8 |
| Mobile air conditioning: recovery | H4.3 | 3.6 | 300 | 100 | 35 |
| Aerosols: hydrocarbons | H5.1 | 2.1 | 200 | 6 | 11 |
| Magnesium production: SO2 | S1.1 | 2.9 | 12 | 0.0 | 0.4 |
| Gas insulated switchgear: recovery | S2.1 | 1.0 | 10 | 3 | 4.1 |
| Aluminium: SWPB conversion | P1.1.1 | 5.2 | 228 | -33 | -2.3 |
| Aluminium: SWPB retrofit | P1.1.2 | 1.3 | 13 | -4 | -2.4 |
| Aluminium: VSS conversion | P1.2.1 | 1.0 | 548 | 0 | 48 |
| Aluminium: VSS retrofit | P1.2.2 | 0.3 | 13 | -1 | -0.3 |
| Semiconductors: CVD $NF_3$ | P2.1 | 9.7 | 532 | 251 | 31 |
| Semiconductors: etch-alt. chem | P2.2 | 1.3 | 0 | 0 | 0.0 |
| Semiconductors: etch-oxidation | P2.3 | 2.6 | 231 | 208 | 89 |

**Table 36 Abatement costs (in deflated 1990 prices) for emission reduction options for the 2010 baseline with different discount rates (DR) - least cost order for DR=4%.**

| measure | code | abated emiss [MT $CO_2$ eq / yr] | Abatemnt Cost [€/ t $CO_2$ eq] DR=2% | abatemnt cost [€/ t $CO_2$ eq] DR=4% | abatemnt cost [€/ t $CO_2$ eq] DR=6% |
|---|---|---|---|---|---|
| Aluminium: SWPB retrofit | P1.1.2 | 1.3 | -2.2 | -2.1 | -2.0 |
| Aluminium: SWPB conversion | P1.1.1 | 5.2 | -2.5 | -2.0 | -1.5 |
| Aluminium: VSS retrofit | P1.2.2 | 0.3 | -0.7 | -0.2 | 0.3 |
| Semiconductors: etch-alt. chem | P2.2 | 1.3 | 0.0 | 0.0 | 0.0 |
| HFC-23: oxidation | H1.1 | 6.8 | 0.2 | 0.2 | 0.2 |
| Magnesium production: SO2 | S1.1 | 2.9 | 0.3 | 0.3 | 0.4 |
| Foam PU-one component: hydrocarbons | H2.7.1 | 3.5 | 0.3 | 0.4 | 0.4 |
| Industrial food refrig.: hydrocarbons a. NH3 | H3.3.1 | 2.4 | 0.5 | 2.4 | 4.5 |
| Industrial refrigeration: hydrocarbons a. NH3 | H3.4.1 | 1.4 | 0.5 | 2.4 | 4.5 |
| Foam PU-pipe in pipe: pentane | H2.5.1 | 0.1 | 2.3 | 2.7 | 3.1 |
| Domestic refrigeration: hydrocarbons | H3.1.1 | 1.1 | 2.6 | 3.0 | 3.4 |
| Gas insulated switchgear: recovery | S2.1 | 1.0 | 3.5 | 3.6 | 3.7 |
| Foams XPS: carbon dioxide | H2.9.1 | 6.3 | 4.8 | 4.9 | 5.0 |
| Mobile air conditioning: leakage red. | H4.2 | 6.6 | 5.1 | 5.9 | 6.8 |
| Aerosols: hydrocarbons | H5.1 | 2.1 | 8.7 | 9.7 | 11 |
| Foam PU-spray: water | H2.6.1 | 1.4 | 18 | 18 | 18 |
| Foam PU-flexibl. faced laminate: pentane | H2.3.1 | 0.8 | 21 | 21 | 21 |
| Mobile air conditioning: carbon dioxide | H4.1 | 8.8 | 19 | 22 | 25 |
| Foam PU-blocks: pentane | H2.8.1 | 0.9 | 26 | 27 | 28 |
| Semiconductors: CVD NF3 | P2.1 | 9.7 | 26 | 27 | 27 |
| Foam PU-discontinuous panels: pentane | H2.4.1 | 0.7 | 27 | 28 | 28 |
| Transport refrigeration: leak reduction | H3.5.1 | 2.8 | 28 | 29 | 29 |
| Foam PU-continuous panels: pentane | H2.2.1 | 0.2 | 29 | 29 | 29 |
| Mobile air conditioning: recovery | H4.3 | 3.6 | 30 | 31 | 32 |
| Stationary air conditioning DX: leak reduction | H3.6.2 | 0.6 | 38 | 38 | 39 |
| Aluminium: VSS conversion | P1.2.1 | 1.0 | 36 | 42 | 48 |
| Stationary air conditioning chiller: HC &NH3 | H3.7.1 | 0.7 | 40 | 43 | 46 |
| Commercial refrigeration: leakage reduction | H3.2.2 | 1.7 | 46 | 47 | 48 |
| Industrial food refrig: leakage reduction | H3.3.2 | 1.0 | 53 | 54 | 54 |
| Industrial refrigeration: leakage reduction | H3.4.2 | 0.6 | 53 | 54 | 54 |
| Foam PU-appliances: pentane | H2.1.1 | 0.2 | 61 | 63 | 64 |
| Semiconductors: etch-oxidation | P2.3 | 2.6 | 77 | 78 | 79 |
| Domestic refrigeration: recovery | H3.1.2 | 0.8 | 78 | 78 | 78 |
| Commercial refrig.: hydrocarbons a. NH3 | H3.2.1 | 4.3 | 76 | 80 | 84 |
| Stationary air conditioning DX: hydrocarbons | H3.6.1 | 1.4 | 96 | 99 | 103 |
| Stationary air conditioning chiller: leak reduct. | H3.7.2 | 0.3 | 149 | 150 | 152 |

**Table 37 Aggregated costs in fields of application for emission reductions for the 2010 baseline (1990 euros and 4% discount rate).**

| **Set of measures** | **Abated emissions [MT $CO_2$ eq.]** | **abated frac [%]** | **Weighted mean of abatement costs [€ / t $CO_2$ eq.]** |
|---|---|---|---|
| HFC23- thermal oxidation | 6.8 | 95 | 0.2 |
| PU alternatives | 7.7 | 95 | 13.5 |
| XPS carbon dioxide | 6.3 | 100 | 4.9 |
| Domestic refrigeration HC | 1.1 | 100 | 3.0 |
| Mob airco leak red. | 6.6 | 37 | 5.9 |
| Aerosols alternatives | 2.1 | 30 | 9.7 |
| $SF_6$ magnesium | 2.9 | 100 | 0.3 |
| $SF_6$ GIS | 1.0 | 25 | 3.6 |
| PFC-Al SWPB conversion | 5.2 | 97 | -0.5 |
| PFC semiconductor alt. chem. | 1.3 | 8 | 0.0 |
| **ALL OPTIONS** | **40.9** | **54** | **4.9** |

**Table 38 Emission sources (2010 baseline) not analysed in respect to costs.**

| **Process** | **Emissions [MT $CO_2$]** |
|---|---|
| HFCs: MDIs | 2.9 |
| HFCs: Solvents | 1.9 |
| HFCs: Fire-Fighting | 0.3 |
| HFCs: Manufacturing and Distribution | 2.6 |
| $SF_6$: Other uses | 10.5 |
| $SF_6$: Manufacturing and Distribution | 1.2 |
| PFCs: Other uses | 5.2 |
| ALL OPTIONS | **24.6** |

# 5 Fields for future research

A number of relevant issues for further research were identified:

- A detailed analysis of country specific factors influencing emission abatement costs for certain options, e.g. building codes, climate, economic structure of sub-sectors, energy prices, and electricity mixes. Special focus could be put on thermal insulation foams and refrigeration and air conditioning comprising:
  - A detailed comparison of cost and energy efficiency performance of different thermal insulation materials in selected typical applications,
  - A survey creating a database on banked amounts of refrigerants in different applications per EU member state and accession country,

  - A detailed comparison of cost and energy efficiency performance of different refrigerants in selected typical applications, and
  - A detailed analysis of costs of different concepts for leakage rate reduction and fluid recovery.

- An assessment of technical options and costs of emission reduction options for HFCs for MDI’s, general aerosols, fire fighting and manufacturing and distribution losses of HFCs, PFCs and $SF_6$.
- An exploratory survey of new, military and currently unrecognised sources of HFCs, PFCs and $SF_6$.
- A feasibility study of a mandatory reporting system for the production, use and emission of HFCs, PFCs and $SF_6$ on a company level.
- An assessment of the effects of direct and indirect subsidies on emission levels of HFCs, PFCs and $SF_6$, e.g. in the agricultural (food storage) and transportation (transport refrigeration) sectors.
- A detailed feasibility study for a European system for emission trading of HFCs, PFCs and $SF_6$.

# 6 Summary and Conclusion

It is estimated that HFC, PFC and $SF_6$ emissions in Europe contributed roughly 70 million tons of $CO_2$ equivalents in 1995. It is projected that European emissions of HFCs, PFCs and $SF_6$ will grow by roughly 2/3 from 1995 to 2010 if no additional measures. This baseline already takes into account a significant decline of emissions from primary aluminium production and HCFC production (HFC-23). These emissions contributed about 1.8% to all European greenhouse emissions in 1995 and are projected to grow to a share of of roughly 3% in 2010 if not further restricted and other greenhouse gas emissions remain constant (Figure 4). Most of this growth is likely to occur in HFCs. Emissions of HFCs in 2010 will still be far from saturation as banked amounts of HFCs in air conditioning and refrigeration equipment will still be far from maturity and most emissions associated with the decommissioning of equipment will not yet be relevant due to the young equipment population. The amounts of HFCs banked in foams will also be far below maturity in 2010. Emissions in the subsequent commitment periods of the Kyoto Protocol are thus likely to be significantly above values for the 2008-2012 period.

If the projected increase of emissions of fluorinated greenhouse gases until 2010 indeed takes place additional emission cuts will have to be carried out elsewhere to compensate for this growth. It is a goal of the main study “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change” to numerically determine the least cost solution to this problem across different sectors of the economy.

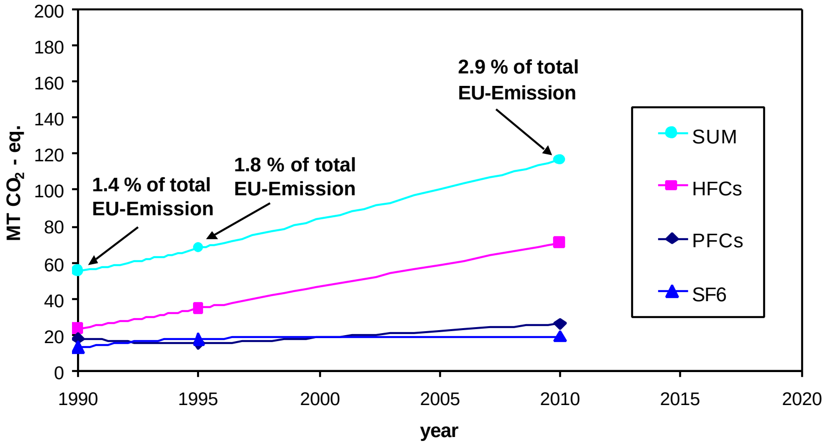

**Figure 4 Temporal evolution of European emissions of HFCs, PFCs and $SF_6$**

The definition of baseline scenarios until 2010 for some sub-sectors requires decisions that cannot be fully justified on a scientific base. Baseline scenarios are thus notoriously sensitive to arbitrary or systematic manipulations.

A number of emission abatement measures was assessed economically as part of this study. A transparent set of cost data is presented for HFCs, PFCs and $SF_6$ in Europe. Figure 5 displays the respective supply curve of emission reduction units in 2010. A least cost policy would attempt to start with low cost options and continue up to certain maximum threshold value. The study identifies a package of measures (roughly 40 MT

$CO_2$ eq. / yr) at a weighted mean cost of roughly €5 per ton of $CO_2$ eq. If the reduction commitment by the European semiconductor industry is also fully included, EU emissions of HFCs, PFCs and $SF_6$ could be stabilised at 1995 levels until 2010. Taking into account the reduction options analysed by this study, significant steps beyond stabilisation become available at marginal abatement costs starting at about €30 per ton of $CO_2$ eq. However, further research and ongoing product development, e.g. in refrigeration and air conditioning, is likely to further increase the portfolio of low cost options.

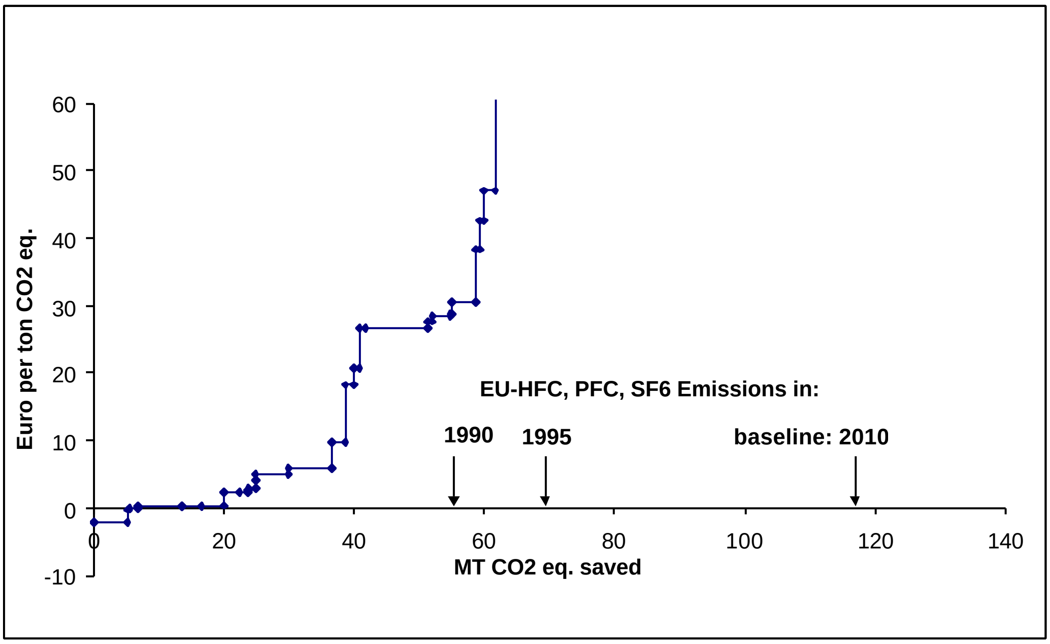

**Figure 5 Marginal abatement cost (1990 Euros) curve for projected European emissions of HFC, PFC and $SF_6$ in 2010. Based on Table 36.**

The analysis of emission abatement options has remained somewhat incomplete due to the limited amount of available technical information on such options in certain fields which together are projected to contribute emissions of about 25 MT $CO_2$ eq. in 2010. The applications that require further study most urgently are: aerosols, solvents, metered dose inhalers and various poorly characterised sources of $SF_6$ and PFCs. Significant potential for low cost abatement options may exists within these applications.

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# 8 Sectoral GWPs

Mean global warming potentials (100 years) [IPCC, 1996] in different applications. Modified after March [1998].

| Application | GWP |
|---|---|
| HFC-Manuf. & Distribution | 1,300 |
| HFC-23 | 11,700 |
| XPS-foams (90% 134a / 10 % 152a) | 1,180 |
| PU/PIR-foams | 815 |
| DOM REF | 1,300 |
| COM & TRANS REF | 2,700 |
| FA IND & GEN IND | 2,200 |
| AC WAT & DISTR | 2,600 |
| Mobile AC | 1,300 |
| Aerosols | 1,300 |
| MDI’s | 1,700 |
| Solvents | 810 |
| Fire-fighting | 2,900 |
| $SF_6$ | 23,900 |
| PFC (expressed as $CF_4$ eq.) | 6,500 |

# 9 List of abbreviations

| | |
|---|---|
| AC | Air Conditioning |
| CFC | Chlorofluorocarbon |
| CWPB | Center Worked Prebake |
| DR | Discount Rate |
| EAA | European Aluminium Association |
| EECA | European Electronic Components Manufacturers Association |
| EF | Emission Factor |
| GWP | Global Warming Potential |
| GIS | Gas Insulated Switchgear |
| HFC | Hydrofluorocarbon |
| HSS | Horizontal Stud Søderberg |
| IEA | International Energy Agency |
| MAC | Mobile Air Conditioning |
| MDI | Metered Dose Inhaler |
| OCF | One Component Foam |
| PFC | Perfluorocarbon |
| PFPB | Pointfeeder Prebake |
| PIR | Polyisocyanurate |
| PTFE | Polytetrafluoroethene |
| PU | Polyurethane |
| REF | Refrigeration |
| SAC | Stationary Air Conditioning |
| SWPB | Side Worked Prebake |
| UNFCCC | United Nations Framework Convention on Climate Change |
| VSS | Vertical Stud Søderberg |
| XPS | Extruded Polystyrene |

# 10 List of reviewers

During the process of writing this study opportunity to comment was given to a number of people, among which:

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