International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

Interim Report **IR-05-056**

The GAINS Model for Greenhouse Gases – Version 1.0: HFC, PFC and SF_6

Antti Tohka

Approved by

Markus Amann
Program Leader
Transboundary Air Pollution Program
(amann@iiasa.ac.at)

October 2005

Abstract

Many of the traditional air pollutants and greenhouse gases have common sources, offering a cost-effective potential for simultaneous improvements of traditional air pollution problems and climate change. A methodology has been developed to extend the RAINS integrated assessment model to explore synergies and trade-offs between the control of greenhouse gases and air pollution. With this extension, the GAINS (**G**HG-**A**ir pollution **IN**teraction and **S**ynergies) model will allow the assessment of emission control costs for the six greenhouse gases covered under the Kyoto Protocol (CO_2, CH_4, N_2O and the three F-gases) together with the emissions of air pollutants SO_2, NO_x, VOC, NH_3 and PM. This report describes the first implementation (Version 1.0) of the model extension model to incorporate emissions of the F-gases, i.e., HFC, PFC and SF_6.

GAINS Version 1.0 assesses 230 options for reducing F-gas emissions from the various source categories. It quantifies for 43 countries/regions in Europe country-specific application potentials of the various options in the different sectors of the economy, and estimates the societal resource costs of these measures. Mitigation potentials are estimated in relation to an exogenous baseline projection that reflects current planning.

The initial implementation of GAINS 1.0 estimates for 1995 total F-gas emissions in the European model domain (39 countries including the European part of Russia) at around 87 Mt CO_2eq. With current legislation emissions are expected to increase by a factor two in 2020, due to the expected increase in HFC emissions from mobile air conditioning and refrigerating. 34 mitigation options for F-gases have been identified and implemented in GAINS 1.0. Full implementation of these options could reduce in 2020 total European F-gas emissions by more than 70 percent (compared to the current legislation baseline projection), which would keep these emissions below their 1995 levels. Marginal costs of these options range from 0.1 to 64 €/tCO_2eq. More than half of these options have costs below 20 €/tCO_2eq.

Uncertainties in the estimates of emissions (and hence control costs) are large due to uncertainties in emission factors, the future penetration of technologies and abatement measures as well as lack of data on activities in a number of countries.

Acknowledgements

The author gratefully acknowledges the financial support for his work received from the Netherlands' Ministry for Housing, Spatial Planning and the Environment.

The author is also indebted to Martin Adams and Judith Bates (AEA-Technology, Harwell, UK), Jochen Harnisch (ECOFYS, Netherlands) and Kees Peek (RIVM) for providing comments on a draft version of the report.

About the author

During his stay at the International Institute for Applied Systems Analysis (IIASA) from 2003 to 2004, Antti Tohka has worked with the Transboundary Air Pollution project. After his stay at IIASA he returned to the Finnish Environment Institute in Helsinki.

Table of contents

1 Introduction 6

1.1 Interactions between air pollution control and greenhouse gas mitigation 6

1.2 GAINS: The RAINS extension to include greenhouse gases 7

1.3 Objective of this report 7

1.4 Structure of the report 7

2 Methodology 8

2.1 Introduction 8

2.2 The RAINS methodology for air pollution 8

2.3 Emission calculation in GAINS 9

2.4 Cost calculation in GAINS 10

3 Emission estimates 14

3.1 Introduction 14

3.2 Emission source categories 14

3.3 Emission factors 15

4 Emission control options and costs 34

4.1 Options and costs of controlling HFC emissions 34

4.2 Options and costs of controlling PFC emissions 39

4.3 Options and costs of controlling SF_6 emissions 41

5 Interactions with other pollutants 43

6 Results 44

6.1 Historic emissions 44

6.2 Projections of future emissions 48

6.3 Costs estimates 58

7 Conclusions 63

Annex 1 67

1 Introduction

1.1 Interactions between air pollution control and greenhouse gas mitigation

Recent scientific insights open new opportunities for an integrated assessment that could potentially lead to a more systematic and cost-effective approach for managing traditional air pollutants simultaneously with greenhouse gases.

- Many of the traditional air pollutants and greenhouse gases have common sources, offering a cost-effective potential for simultaneous improvements for both air pollution problems and climate change. For instance, climate change measures that aim at reduced fossil fuel combustion will have ancillary benefits for regional air pollutants (Syri *et al.*, 2001). In contrast, some ammonia abatement measures can lead to increased nitrous oxide (N_2O) emissions, while structural measures in agriculture could reduce both regional air pollution and climate change. Methane (CH_4) is both an ozone (O_3) precursor and a greenhouse gas. Hence, CH_4 abatement will have synergistic effects and some cheap abatement measures may be highly cost effective.

- Some air pollutants (e.g., tropospheric ozone and aerosols) are also important greenhouse gases and exert radiative forcing. As summarized by the Intergovernmental Panel on Climate Change (IPCC), changes in tropospheric ozone were found to have the third-largest positive radiative forcing after carbon dioxide (CO_2) and CH_4 (Houghton *et al.*, 2001), while sulphate aerosols exert negative forcing. Furthermore, understanding is growing on the role of carbonaceous aerosols, suggesting warming effects for black carbon and cooling effects for organic carbon.

- Other air pollutants such as ozone, nitrogen oxides (NO_x), carbon monoxide (CO) and volatile organic compounds (VOC) act as indirect greenhouse gases influencing (e.g., via their impact on OH radicals) the lifetime of direct greenhouse gases (e.g., CH_4 and hydrofluorocarbons). Global circulation models have only begun to incorporate atmospheric chemistry and account fully for the important roles of conventional air pollutants.

It is clear that interactions between air pollutants and radiative forcing can be multiple and can act in opposite directions. For instance, increases in NO_x emissions decrease (via OH radicals) the lifetime of CH_4 in the atmosphere and thereby cause reduced radiative forcing. At the same time, NO_x emissions produce tropospheric ozone and increase radiative forcing. A further pathway leads to increased nitrogen deposition that may cause, via the fertilisation effect, enhanced growth of vegetation. This in turn offers an increased sink for carbon – although the net effect cannot yet be fully quantified.

Time is an important factor in the context of mitigation. While the climate change benefits (i.e., temperature decreases) take effect on the long-term, reduced air pollution will yield benefits for human health and vegetation also in the short and medium term.

1.2 GAINS: The RAINS extension to include greenhouse gases

The Regional Air Pollution INformation and Simulation (RAINS) model has been developed at the International Institute for Applied Systems Analysis (IIASA) as a tool for the integrated assessment of emission control strategies for reducing the impacts of air pollution. The present version of RAINS addresses health impacts of fine particulate matter and ozone, vegetation damage from ground-level ozone as well as acidification and eutrophication. To explore synergies between these environmental effects, RAINS includes emission controls for sulphur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOC), ammonia (NH_3) and fine particulate matter (PM).

Considering the new insights into the linkages between air pollution and greenhouse gases, work has begun to extend the multi-pollutant/multi-effect approach that RAINS presently uses for the analysis of air pollution to include emissions of greenhouse gases. This could potentially offer a practical tool for designing national and regional strategies that respond to global and long-term climate objectives (expressed in terms of greenhouse gas emissions) while maximizing the local and short- to medium-term environmental benefits of air pollution. The emphasis of the envisaged tool is on identifying synergistic effects between the control of air pollution and the emissions of greenhouse gases.

The new tool is termed 'GAINS': **G**HG-**A**ir pollution **IN**teractions and **S**ynergies. It is not proposed at this stage to extend the GAINS model towards modelling the climate system.

1.3 Objective of this report

The objective of this report is to describe a first version of the GAINS model (Version 1.0) related to emission control options for hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) and the associated costs. Other reports have been prepared for the other Kyoto greenhouse gases (CO_2, CH_4, N_2O) and are available on the Internet (http://www.iiasa.ac.at/rains/gains/index.html).

1.4 Structure of the report

This report has the following structure: Section 2 describes the methodology to extend the RAINS air pollution model to include emissions of greenhouse gases and presents the calculation methods for emissions and costs. Section 3 reviews the different sources of F-gas emissions. Section 4 describes options and costs for mitigating F-gas emissions in the various sectors. Section 5 discusses interactions between the control of F-gas emissions and of other air pollutants. Section 6 presents initial results from the first version of the GAINS model. Conclusions are drawn in Section 7.

2 Methodology

2.1 Introduction

A methodology has been developed to assess, for any exogenously supplied projection of future economic activities, the resulting emissions of greenhouse gases and conventional air pollutants, the technical potential for emission controls and the costs of such measures, as well as the interactions between the emission controls of various pollutants. This new methodology revises the existing mathematical formulation of the RAINS optimisation problem to take account of the interactions between emission control options of multiple pollutants and their effects on multiple environmental endpoints.

This Section first describes the existing RAINS methodology. Subsequently, the method to calculate future emissions is explained. Then the costing methodology is described and the new formulation of the optimisation method is summarised.

2.2 The RAINS methodology for air pollution

The Regional Air Pollution Information and Simulation (RAINS) model developed at the International Institute for Applied Systems Analysis (IIASA) combines information on economic and energy development, emission control potentials and costs, atmospheric dispersion characteristics and environmental sensitivities towards air pollution (Schöpp *et al.*, 1999). The model addresses threats to human health posed by fine particulates and ground-level ozone as well as risk of ecosystems damage from acidification, excess nitrogen deposition (eutrophication) and exposure to elevated ambient levels of ozone. These air pollution related problems are considered in a multi-pollutant context (Figure 2.1) quantifying the contributions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), non-methane volatile organic compounds (VOC), and primary emissions of fine (PM2.5) and coarse (PM10-PM2.5) particles. A detailed description of the RAINS model, on-line access to certain model parts as well as all input data to the model can be found on the Internet (http://www.iiasa.ac.at/rains).

The RAINS model framework makes it possible to estimate, for a given energy- and agricultural scenario, the costs and environmental effects of user-specified emission control policies. Furthermore, a non-linear optimisation mode has been developed to identify the cost-minimal combination of emission controls meeting user-supplied air quality targets, taking into account regional differences in emission control costs and atmospheric dispersion characteristics. The optimisation capability of RAINS enables the development of multi-pollutant, multi-effect pollution control strategies. In particular, the optimisation can be used to search for cost-minimal balances of controls of the six pollutants (SO_2, NO_x, VOC, NH_3, primary $PM_{2,5}$, primary $PM_{10\text{-}2.5}$ (= PM coarse)) over the various economic sectors in all European countries that simultaneously achieve user-specified targets for human health impacts (e.g., expressed in terms of reduced life expectancy), ecosystems protection (e.g., expressed in terms of excess acid and nitrogen deposition), and maximum allowed violations of WHO guideline values for ground-level ozone.

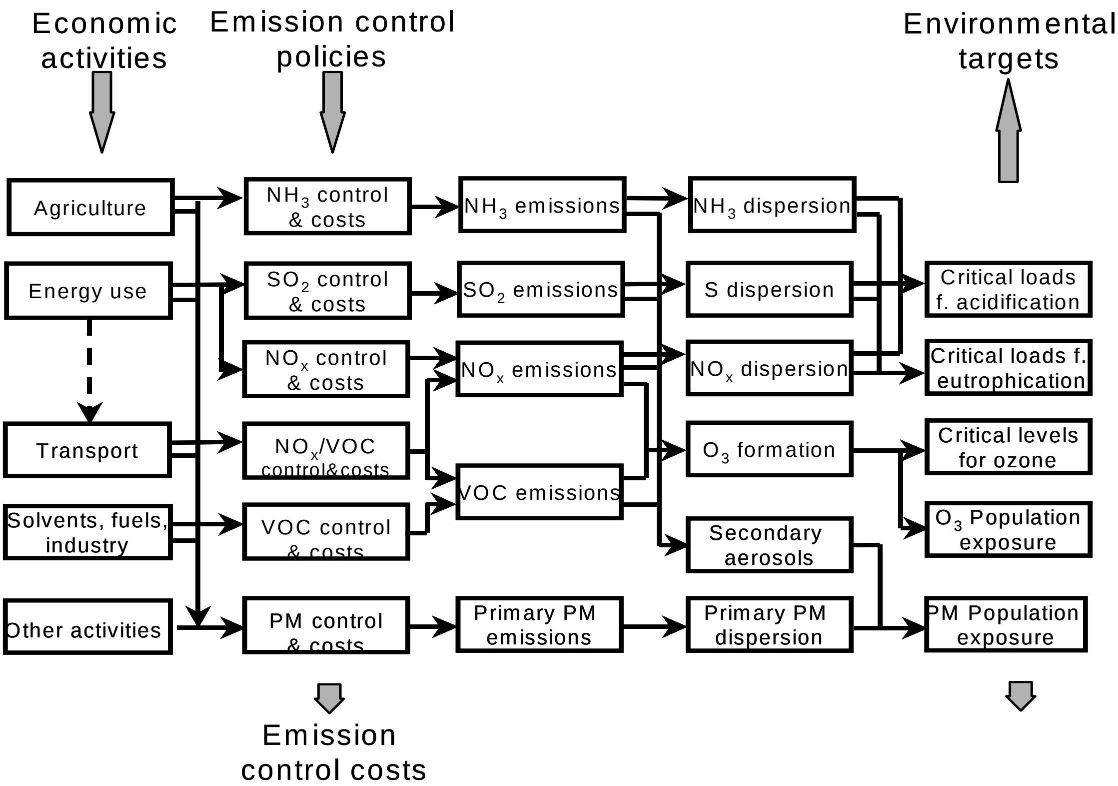

Figure 2.1: Information flow in the RAINS model

2.3 Emission calculation in GAINS

The methodology adopted for the estimation of current and future greenhouse gas emissions and the available potential for emission controls follows the standard RAINS methodology. Emissions of each pollutant p are calculated as the product of the activity levels, the "uncontrolled" emission factor in absence of any emission control measures, the efficiency of emission control measures and the application rate of such measures:

$$E_{i,p} = \sum_{j,k,f} E_{i,j,f,t} = \sum_{j,k,m} A_{i,j,k} ef_{i,j,t} (1 - eff_t) X_{i,j,f,t} \qquad \text{Equation 2.1}$$

where

i,j,t,f	Country, sector, abatement technology, fuel,
$E_{i,p}$	Emissions of the specific pollutant p in country i,
A	Activity in a given sector,
ef	"Uncontrolled" emission factor,
$eff_{k,p}$	Reduction efficiency of the abatement option k, and
X	Actual implementation rate of the considered abatement.

If no emission controls are applied, the abatement efficiency equals zero ($eff_{k,p} = 0$) and the application rate is one ($X = 1$). In that case, the emission calculation is reduced to simple multiplication of activity rate by the "uncontrolled" emission factor.

For projecting emissions into the future, the "uncontrolled" emission factor is assumed to be constant over time, but activity levels may change as a result of exogenous autonomous developments. For example, a higher number of cars using mobile air conditioning or an increase in primary aluminium production will result in higher activity levels of the specific source category. Declines in emissions due to targeted emission control measures are reflected in the GAINS model through the actual implementation rate X of the considered option. Cases where there is clear evidence that average emission factors change over time due to autonomous (policy independent) developments (e.g., increased volumes of refrigerant used per refrigerator) are represented in GAINS as transitions to different source categories with different uncontrolled emission factors. However, in view of the uncertainty surrounding the future development of emission factors for the various F-gases, as well as the fact that it is not clear whether potential changes in emission factor are an anticipation of expected policies or not, this option has not been implemented in GAINS 1.0.

A particular characteristic of a large fraction of the HFC emissions is that they result both from the releases of HFC during the lifetime of the appliance (e.g., leakage from refrigerators) as well as from their scrapping at the end of life. The former emissions are referred to as "emissions banked in equipment" and the latter as "emissions from scrapped equipment", i.e. end-of-life emissions. Based on external calculations of the contributions from these two fractions, GAINS 1.0 applies one single emission factor that combines both sources.

2.4 Cost calculation in GAINS

2.4.1 General approach

The cost evaluation in the RAINS/GAINS models attempts to quantify the values to society of the resources diverted in order to reduce emissions in Europe (Klimont *et al.*, 2002). In practice, these values are approximated by estimating costs at the production level rather than at the level of consumer prices. Therefore, any mark-ups charged over production costs by manufacturers or dealers do not represent actual resource use and are ignored. Any taxes added to production costs are similarly ignored as subsidies since they are transfers and not resource costs.

A central assumption in the GAINS cost calculation is the existence of a free market for (abatement) equipment throughout Europe that is accessible to all countries at the same conditions. Thus, the capital investments for a certain technology can be specified as being independent of the country. Simultaneously, the calculation routine takes into account several country-specific parameters that characterise the situation in a given region. For instance, these parameters may include average operating hours, fuel prices, capacity/vehicles utilization rates and emission factors.

Expenditures for emission controls are differentiated into:

- investments,
- fixed operating costs, and
- variable operating costs.

GAINS calculates from these three components annual costs per unit of activity level. Subsequently, these costs are expressed per ton of pollutant abated.

Some of the parameters are considered common to all countries. These include technology-specific data, such as removal efficiencies, unit investment costs, fixed operating and maintenance costs, as well as parameters used for calculating variable cost components such as the extra demand for labour, energy, and materials.

Country-specific parameters characterise the type of capacity operated in a given country and its operation regime. These parameters include the average size of installations in a given sector, operating hours, annual fuel consumption and mileage for vehicles. In addition, prices for labour, electricity, fuel and other materials as well as cost of waste disposal also belong to that category.

Although based on the same principles, the methodologies for calculating costs for individual sectors need to reflect the relevant differences (e.g., in terms of capital investments). All costs in GAINS are expressed in constant € (in constant prices of the year 2000).

2.4.1.1 Investments

For industrial process sources, investments are related to the activity unit of a given process. For the majority of processes these are annual tons produced. The investment function and annualised investments are given by the following two equations:

$$I = ci^{f} * (1 + r)$$ Equation 2.2

$$I^{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1}$$ Equation 2.3

2.4.1.2 Operating costs

The annual **fixed expenditures** OM^{fix} cover the costs of repairs, maintenance and administrative overhead. These cost items are not related to the actual use of the plant. As a rough estimate for annual fixed expenditures, a standard percentage *f* of the total investments is used:

$$OM^{fix} = I * f$$ Equation 2.2

The **variable operating costs** OM^{var} are related to the actual operation of the plant and may take into account elements such as

- additional demand for labour,

- increased or decreased energy demand for operating the device (e.g., for fans and pumps), and
- waste disposal.

These cost items are calculated with the specific demand λ^x of a certain control technology and its (country-specific) price c^x:

$$OM^{var} = \lambda^l c^l + \lambda^e c^e + ef * \eta * \lambda^d c^d$$ Equation 2.3

Variable operating costs OM^{var} are related to the actual operation of the plant and may take into account elements such as:

- additional demand for labour,
- increased or decreased energy demand for operating the device (e.g., for fans and pumps), and
- waste disposal.

These cost items are calculated with the specific demand λ^x of a certain control technology and its (country-specific) price c^x:

$$OM^{var} = \lambda^l c^l + \lambda^e c^e + ef * \eta * \lambda^d c^d$$ Equation 2.6

where

η	emission removal efficiency,
λ^l	labour demand,
λ^e	additional energy demand
λ^d	demand for waste disposal (per unit of emission reduced),
c^l	labour cost,
c^e	energy price,
c^d	waste disposal cost,
ef	unabated emission factor.

The coefficients λ^l, λ^e, and λ^d relate to one ton of product, and *ef* is the emission factor for the specific pollutant.

2.4.1.3 Unit reduction costs

Unit costs per ton of product

This cost is calculated from the following formula:

$$c_{ton} = I^{an} + OM^{fix} + OM^{var}$$ Equation 2.7

Unit costs per ton of pollutant removed

As for combustion sources, one can calculate costs per unit of emission removed:

$$c_{p_k} = c_{ton} / (ef \quad * \eta \quad)$$ Equation 2.8

The most important factors leading to differences among countries in unit abatement costs are differences in the annual use of the equipment (for example in southern countries air condition equipments are used more than in northern), in electricity prices, in unabated emission factors and in HFC compounds used in individual countries. However, due to general uncertainties and the lack of solid country-specific information, the initial implementation of GAINS 1.0 ignores such differences in the cost calculation. Operating hours and refrigerant blends emission factors are assumed equal for all countries. Unabated sector-specific emission factors are estimated based on the guidelines of the Intergovernmental Panel on Climate Change (IPCC) and comments received during the review meeting on a draft of this report. There is high uncertainty concerning the global warming potentials (GWP) of used refrigerants since they may vary considerably within a sector. Therefore, average values or the most likely blend of GWPs are used when calculating GWPs for a specific sector. No autonomous improvement is assumed to take place in this calculation, except for the refrigerated transport sector.

3 Emission estimates

3.1 Introduction

The man-made greenhouse gases hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) are often summarised as title F-gases. These F-gases account for approximately one percent of the direct radiative forcing from greenhouse gases, but business as usual scenarios suggest a rapid increase in their importance. Harnisch and Hendriks (2000) estimated that in the year 2010 F-gases may account for around three percent of greenhouse gas emissions in the EU-15. This is due to an increased use of air conditioning, refrigeration, foam and aerosol applications as substitutes for chlorofluorocarbons (CFCs) such as hydrochlorofluorocarbons (HCFCs), which are banned by the Montreal Protocol.

This chapter describes the emission source categories, the emission factors and the methodology used for estimating the current and future emissions of F-gases.

3.2 Emission source categories

Sources, magnitudes and projections of future F-gas emissions differ significantly between countries and studies, mainly due to structural differences and the timing of the substitution of ozone depleting substances. According to the EDGAR inventory (RIVM/TNO, 2004; Olivier, 2002), two-thirds of the global HFC emissions in 1995 (126 Mt CO_2eq) resulted from the production of HCFC-22 (chlorodifluoromethane). The remainder resulted from various usages of HFCs. Around 70 percent of global PFC emissions (99 Mt CO_2eq) came from primary aluminium production and the remainder originated from the usage of PFC.

Some two-thirds of global SF_6 emissions (144 Mt CO_2eq) resulted from the manufacturing of electric equipment, equipment use in utilities and other electrical equipment use. The remainder came from a variety of sources such as the production of magnesium. First global estimates for future SF_6 and PFC were made in the nineties (Victor and MacDonald, 1999). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (Nakicenovic *et al.*, 2002) included updated estimates for HFC, PFC and SF_6 indicating that, in the worst case (the B2 scenario), global PFC and SF_6 emission might increase by 45 to 70 percent in 2020 compared to 1990.

The uncertainty in individual national estimates is significant. Data available from the United Nations Framework Convention on Climate Change (UNFCCC) databases (UNFCCC, 2004) report for 1995 for the Annex I countries HFC emissions of 124 Mt CO_2eq, PFCs of 78 Mt CO_2eq and SF_6 of 100 Mt CO_2eq). However, for the year 1995, only 60 percent of the countries submitted data. Nonetheless, some countries have provided inventories in the common reporting format (CRF) with great details on the sector-specific split. Yet, most countries have not provided this information in sufficient detail and it is difficult to draw conclusions on the importance of individual sources in Europe.

Bearing this in mind, Table 3.1 summarises the most important anthropogenic activities in Europe that lead to the emission of F-gases and their relative importance on a European level. However it should be noted that the importance of certain emission sectors, especially of HCFC-22 production, aerosol use (including metered dose inhalers), primary aluminium production and of some SF_6 sources, can be rather different across countries.

Table 3.1: Importance of the sources of HFC, PFC and SF6 emissions for 1995 and 2020 in Europe as estimated by GAINS 1.0

	1995	2020
HCFC-22 production	1	2
Industrial refrigeration	3	1
Commercial refrigeration (supermarkets, etc.)	3	1
Transport refrigeration	3	3
Stationary air-conditioning	3	2
Small hermetic refrigerators	3	3
Mobile air-conditioning	3	1
Aerosols (including metered dose inhalers)	3	3
One component foam	3	3
Other foams	3	3
Manufacturing and distribution of HFCs	3	3
Other use of HFC	3	3
Primary aluminium production	1	1
Semiconductor industry, PFC use in CVD and etching	3	2
High (and mid) voltage switches	2	3
Magnesium processing	3	3
Manufacturing and distribution of SF_6	3	3
Other use of SF_6	3	3

1: >10% of total emissions

2: 6-10% of total emission

3: <6% of total emissions

3.3 Emission factors

3.3.1 Hydrofluorocarbon (HFC) emissions

During the 1990s, many sectors that formerly used CFC gases changed rapidly to applications employing HFCs to comply with the Montreal Protocol and its subsequent amendments that demanded a phase out of ozone depleting substances (ODS). The IPCC Guidelines for National Greenhouse Gas Inventories (Tier 2: Advanced Methodology for Estimating Emissions) (Houghton *et al.*, 1997a and 1997b) introduced two different methods to estimate emissions: a “bottom-up” and a “top-down” approach.

The recommended method depends on the quality of available data. In the "bottom-up" approach, emissions of each individual HFC and PFC chemical are calculated based on equipment numbers or detailed use data. Alternatively, in the "top-down" approach emissions are estimated based on the levels of consumption and the emission characteristics of various processes and equipment (taking current service and recovery practices into account). For the GAINS 1.0 model, the "top-down" approach offers sufficient detail. Activities that emit HFC have been divided into 12 different sectors, six of which are related to refrigeration and air conditioning. In the remainder, each of the 12 sectors will be discussed.

3.3.1.1 HCFC-22 production

HCFC-22 (chlorodifluoromethane) is a gas used in refrigeration and air-conditioning systems, foam manufacturing as a blend component of blowing agents, and the manufacturing of synthetic polymers. Since it is an ozone depleting substance, most developed countries are phasing out HCFC-22 from most end uses with the exception of the use as chemical feedstock.

The production of HCFC-22 involves the reaction of chloroform ($CHCl_3$) and hydrogen fluoride (HF) using antimony pentachloride ($SbCl_5$) as a catalyst. This process generates HFC-23 (trifluoromethane) as a by-product, but the amount varies depending on plant-specific conditions and the amount of HCFC-22 production. HFC-23 has a GWP of 11,700 over a 100-year time horizon, so its potential impact on climate change is significant. With the implementation of the Montreal Protocol, HCFC consumption is gradually eliminated, with reductions from the 1986 base-year levels of 35, 65 and 90 percent in 2004, 2010, and 2015, respectively. Final HCFC consumption phase-out should occur in 2020 (2040 for developing countries).

To calculate HFC emissions, GAINS applies emission factors related to the volume of HCFC-22 production. Activity data are based on reported production levels for historic years (Harnisch and Hendriks, 2000; AEAT, 2003; Schwarz and Leisewitz, 1999; Kokorin and Nakhutin, 2000) and UNEP's phase out schedule for CFC and HCFC products for future years (UNEP, 1997). Emission factors are presented in Table 3.2.

Table 3.2: Calculation of HFC emissions from HCFC production in GAINS

GAINS sectors	HCFC-22	HCFC-22 production		
Activity rate	HCFC-22 production			
Unit	Tons per year			
Data sources	Harnisch and Hendriks (2000); AEAT (2003); Schwarz and Leisewitz (1999); Kokorin and Nakhutin (2000)			
Emission factors				
Sector	Emission control	Emission factor [t HFC-23/ t HCFC-22 produced]	GWP (100 years)	Emission factor [t CO_2eq/ t HCFC-22 produced]
HCFC22	No control	0.02	11,700	2,340
Data sources	Harnisch and Hendriks (2000); AEAT (2003)			

3.3.1.2 Cooling and stationary air conditioning

To capture differences in emissions, mitigation potentials and costs, GAINS 1.0 distinguishes five sub-sectors, i.e., cooling for domestic, commercial, industrial and transport purposes, as well as stationary air-conditioning (Table 3.3). Additional sources, which make only minor contributions to total emissions, such as artificial ice rinks, professional kitchen refrigeration machines and some smaller air conditioning equipment, are included in the category "Other use of HFC".

Table 3.3: Sub-sectors distinguished in GAINS 1.0 for cooling and stationary air conditioning

GAINS sectors	DOM_S	Domestic small hermetic refrigerators, emissions from scrapped equipment
	COMM_B	Commercial refrigeration, emissions banked in equipment
	COMM_S	Commercial refrigeration, emissions from scrapped equipment
	IND_B	Industrial refrigeration, including food and agricultural, emissions banked in equipment
	IND_S	Industrial refrigeration, including food and agricultural, emissions from scrapped equipment
	TRA_REFB	Refrigerated transport, emissions banked in equipment
	TRA_REFS	Refrigerated transport, emissions from scrapped equipment
	AIRCON_B	Stationary air conditioning using water chilling, emissions banked in equipment
	AIRCON_S	Stationary air conditioning using water chilling, emissions from scrapped equipment
Activity rate	Stock of HFC used as refrigerant.	
Unit	HFC tons/year	
Data sources	Annual emission inventories of the Parties submitted to the UNFCCC (http://unfccc.int/program/mis/ghg/submis2003.html); Harnisch and Hendriks (2000); Oinonen and Soimakallio (2001)	

For cooling purposes, different refrigerants were used in the past. CFC-12 (R-12) was used for a temperature range from 0 °C to +10 °C, the CFC/HCFC blend R-502 for low temperatures between -25 °C and -10 °C. HCFC-22 (R-22), the quantitatively most important refrigerant, was used for medium temperatures and for the majority of air-conditioning systems. Due to the phase-out of ozone depleting substances, CFCs and HCFCs are replaced, mainly with the corresponding HFC compounds.

The phase-out schedule depends for individual countries on their status in the Montreal Protocol. Countries operating under Article 5, Paragraph 1 of the Montreal protocol (later in the text Article 5 countries) are entitled to a grace period before phase-out measures have to be implemented. For developed countries, the target years for stabilizing consumption levels are 1989 for CFCs and 1996 for HCFCs. These countries have to completely phase out CFCs in

1996 and HCFCs in 2030. Developing countries have to stabilise their consumption of CFCs in 1990 and HCFCs in 2016 and have to stop using CFCs in 2010 and HCFCs in 2040.

Activity data for the year 2000 have been compiled from various sources (Harnisch and Hendriks, 2000; AEAT, 2003; Schwarz and Leisewitz, 1999; Common Reporting Formats and National Communications to the UNFCCC), assuming an average charge per installation as listed in Table 3.4 below. Estimates of the average charge size are based on Houghton *et al.* (1997b), Pedersen (1998), and Oinonen and Soimakallio (2001). Estimates for the year 2000 are calibrated as the reference year for the EU-25 for HFC, activity levels in all other years are calculated by using growth rates described in Table 3.5.

The saturation year of the sector depends on average equipment lifetime. For commercial refrigeration 2005 has been assumed as the saturation year, and for stationary air conditioning and industrial refrigeration 2010. Due to short equipment lifetime of refrigerated transport, no saturation year was assumed for this source, but a stabilization of the autonomous improvement of equipment after 2000. In the domestic sector, the growth of activity levels follows the development in terms of number of households. After the saturation year, market growth for HFC use no longer depends on the CFC phase out. Uncertainties exist for the period between 2000 and the saturation year, where economic indicators do not accurately reflect changes in HFC use. For GAINS 1.0, a steady annual consumption of refrigerants in new equipment is assumed. Sectoral growth rates are illustrated in Figure 3.1 to Figure 3.4.

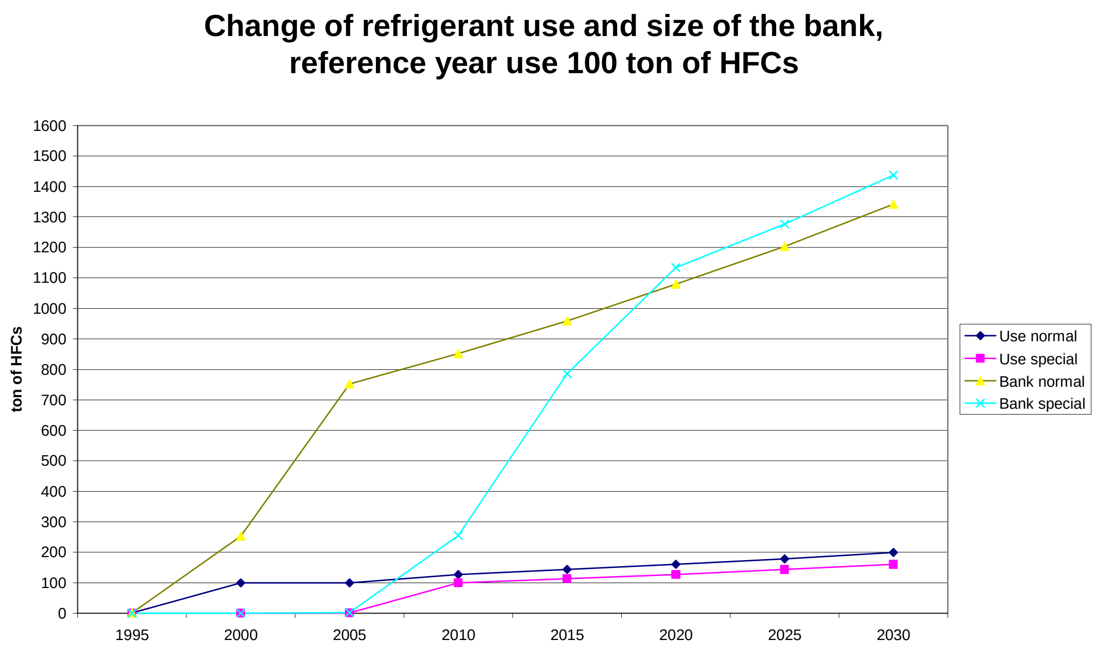

Figure 3.1: Change of refrigerant use and size of the bank in the commercial sector with an assumed saturation year 2005. "Use special" and "bank special" curves refer to the development in countries operating under Article 5, paragraph 1 of the Montreal protocol.

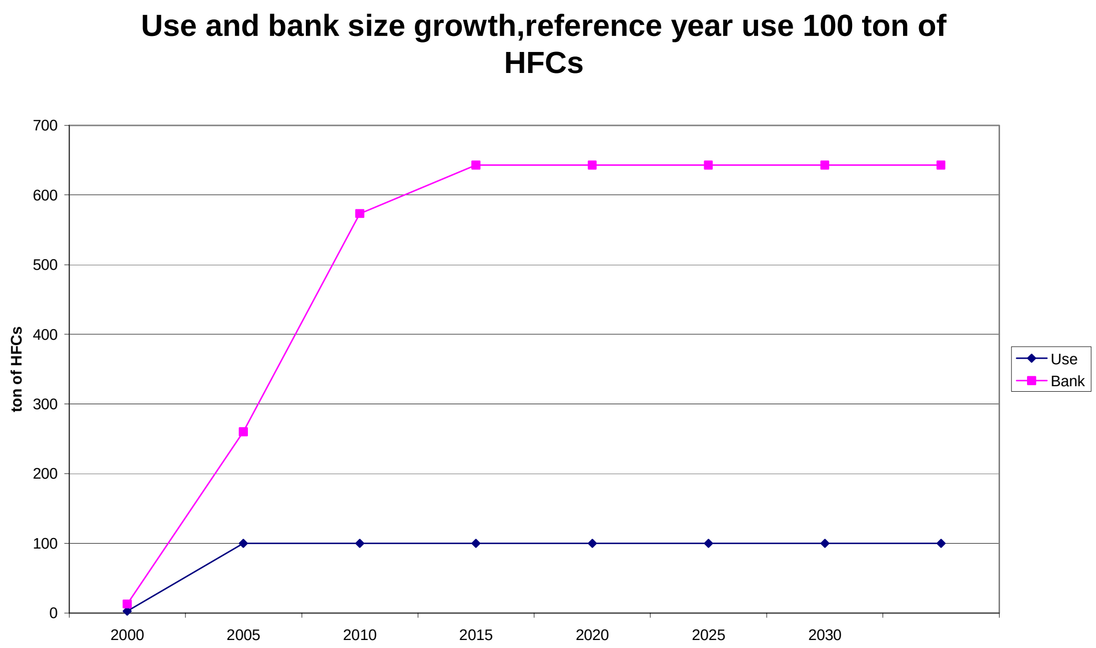

Figure 3.2: Change of refrigerant use and size of the bank in refrigerated transport sector. No difference was made between Article 5 countries and others due to the short lifetime of the equipment and limited amount of manufacturers.

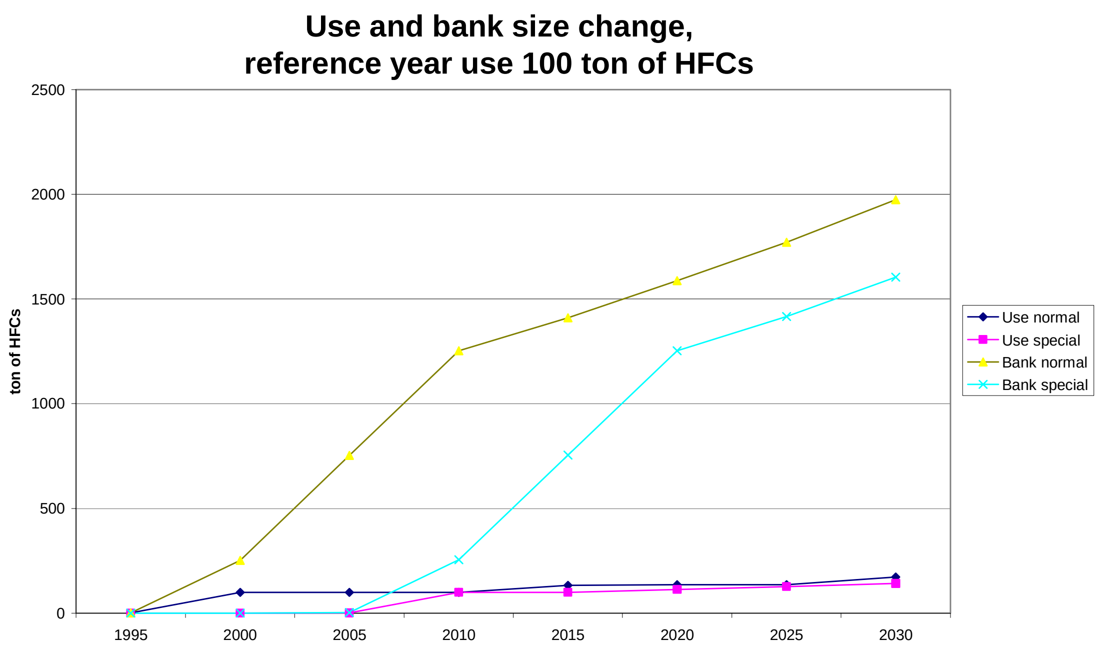

Figure 3.3: Change of refrigerant use and size of the bank in industrial sector (saturation year 2010). "Use special" and "bank special" curves refer to the development in countries operating under Article 5, paragraph 1 of the Montreal protocol.

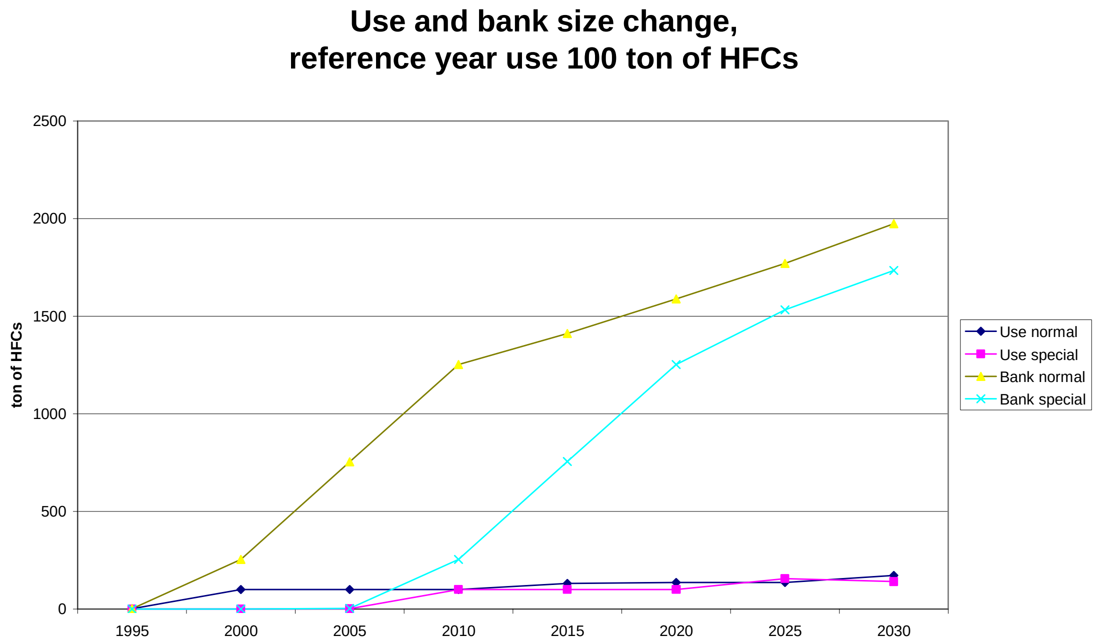

Figure 3.4: Change of refrigerant use and size of the bank in stationary air conditioning sector with an assumed saturation year 2010.

Growth rates and market penetration rates of cooling and air conditioning assumed for the future are listed in Table 3.5. Growth rates are based for the EU-25 on activity forecasts of the baseline scenario of the "Energy Outlook" developed in 2003 by the Directorate General for Energy and Transport of the European Commission (Mantzos *et al.*, 2003; EC, 2003b; p. 59-60). For the non-EU countries, national reports of activity projections have been used. Details on projected fuel consumption and production levels are available from the RAINS website (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/MainPageEmco.htm). Average market growth rates (i.e., the gross value added) for commercial and industrial sectors for the EU-15 were derived from EC (2003; p. 132). The activity pathway for the domestic sector is linked to the development of the number households.

For the F-gases, activity levels comprise the so-called refrigerant bank or stock. This bank describes the average annual stock of refrigerants for a particular application as a function of the (past) sales of refrigerant and the scrapping rate of the application. Due to the complex nature of refrigerant banks, three stages during the life cycle of a refrigerant are distinguished for the calculation of emissions: (i) during installation/manufacture, (ii) during the lifetime of the product, and (iii) at the end of life. Losses during manufacturing and installation are negligible compared to the other losses.

Table 3.4: Losses in specified refrigerant sectors during the life cycle for the different sub-sectors (bank and scrap)

	Domestic DOM	Commercial COMM	Transport refrigerating TRA_REF	Industry IND	Air conditioning AIRCON
Activity	tons HFC	tons HFC	tons HFC	tons HFC	tons HFC
EF during product life (per year) (sub activity bank)	0.01	0.15	0.20	0.15	0.1
EF at decommissioning no control (sub activity scrapped)	1	1	1	1	1
Mean lifetime of equipment (years)	15	10 yrs	7 yrs	15 yrs	15 yrs
Average GWP of refrigerant	1300	2726	2000	2600	1670
Average refrigerant charge [kg HFC/unit]	0.1	30/300[1]	6	80	$60 g/m^{3*}$

*Average charge of refrigerant per cooled m^3

Table 3.5: Average market growth of HFC use in new equipment (1995-2010) and total refrigerant bank (2010-2030) in percent per year in the EU-25 as assumed in GAINS 1.0

GAINS sector	1995-1999	2000-2010**	2010-2020***	2020-2030***
DOM	Sales statistics or HH*	HH	HH	HH
COMM	country specific	0 - 2.4	2.4	2.2
IND	country specific	0	2.4	2.2
TRA_REF	country specific	0	0	0
AIRCON	country specific	0	2.4	2.2

*HH: calculated from the number of households, assuming that every households purchases (on average) 0.105 small hermetic units per year in EU-15 and 0.1 elsewhere.
**average market growth of use in a new equipment
***average market growth of refrigerant bank after saturation year

In almost all refrigerant/air-conditioning sectors, equipment must be refilled annually with new refrigerant, causing significant emissions (typically around 15 percent of the charge per year). HFC emissions are accordingly determined by the losses of refrigerant during the various stages of the life cycle. The above implies that the GAINS emissions for these sectors include emissions during the lifetime and emissions at the end-of-life of the equipment when the equipment is scrapped. Lifetime emissions are a function of the stock (or bank) of HFC in the stock of appliances (i.e., refrigerators or cars with air conditioning).

Basically, emissions are assumed as a fixed percentage of the average stock of HFCs in the appliances. End-of-life emissions depend on the number of appliances being scrapped in that specific year. The number of appliances scrapped depends on the lifetime of the appliances and the HFC use in the past. Table 3.4 summarizes the losses of refrigerants during the life cycle as

[1] 30 for small and 300 for big refrigerators.

percent of the total charge. This table can be used to calculate the emission factors for each sector. For the domestic sector, the emission factor during product life is very low as it is hermetically sealed and does not require refilling during its lifetime.

Example calculation: Lifetime losses of HFC from industrial refrigerators

Size of the charge = 80 kg

Emissions over equipment lifetime = Equipment lifetime (15 years) * charge size (80 kg) * lifetime emission factor (0.15) + size of the charge (80 kg) * end of life emission factor (1) = 15 * 80 * 0.15 + 80 + 1 = 180 (kg) + 80 (kg) = 260 kg

This calculation yields average lifetime emissions of industrial refrigerators are 260 kg, representing total stock and total amount of scrapped HFC in a given year. Average sizes are presented in Table 3.4 for illustrative purposes. Activity unit used in GAINS is not number of equipments, but metric tons of (sector specific) HFC refrigerant.

GAINS models the use of HFCs in the domestic sector as a function of the number of households, the number of fridges per household, the share of HFC-based fridges, and the HFC-charge per fridge. Typically, refrigerant for this sector is not replaced during the appliance's lifetime. With minimal leakage during the equipment lifetime in this sector, emissions are calculated only from the end of life source. However, it is important to distinguish the differences in the GWP of the refrigerants used in the different sectors.

The GWP depends on two factors, the policy choice of the GWPs and the mix of fluids (refrigerants). The GWP is determined by the time horizon (20 years, 100 years or other, see Annex 1) chosen and the reference study, (i.e., the IPCC Second 'SAR' or Third Assessment Report 'TAR'). The UNFCCC has agreed to use the 100 year GWP of the SAR for accounting greenhouse gases and the Kyoto Protocol targets. Therefore, GAINS uses the values of SAR for the whole time horizon to calculate the different GWPs. In the refrigeration sector, the average GWP depends on the mix of fluids since refrigerants with different GWPs are used. Table 3.6 lists the sector-specific GWPs presented in the literature or in CRFs in the UNFCCC. The resulting HFC emission factors for stationary cooling and air conditioning are presented in Table 3.7.

Table 3.6: Examples of different sector specific global warming potentials (GWPs)

GAINS sector	Germany CRF (SAR/ TAR)	France CRF* (SAR/ TAR)	Spain CRF* (SAR /TAR)	Harnich and Hendricks (2000)	EMF-21	AEAT (2003)	Oinonen and Soimakallio (2001)
COMM	2472/2748	3214/3720	2442/2702	2700	2726	2310/2590	3195
TRA_REF	1995/2187	2059/2258	-	2700	2771	2605/2867	3260
IND	2660/2921	3107/3589	-	2200	2171	2047/2291	2490
AIRCON	1470/1564	1456/1545	-	2600	1673	1541/1677	1878

*2003 submissions

**GWP of the refrigerants in new equipment in year 2010

Table 3.7: Calculation of HFC emissions from cooling and stationary air conditioning (no control) in GAINS

GAINS sector	Emission type	Emission factor [t HFC/year/ t bank/use]	GWP (100 years)	Source (if more than one gas)	Emission factor [t CO_2eq/year/ t activity]
DOM	Scrap (end of life)	1	1300		1300
COMM_B	Bank (lifetime)	0.2	2726	EMF-21	545
COMM_S	Scrap (end of life)	1	2726	EMF-21	2726
TRA_REFB	Bank (lifetime)	0.2	2000	own*	400
TRA_REFS	Scrap (end of life)	1	2000	own*	2000
IND_B	Bank (lifetime)	0.15	2490	own**	390
IND_S	Scrap (end of life)	1	2490	own**	2600
AIRCON_B	Bank (lifetime)	0.1	1627	EMF-21	163
AIRCON_S	Scrap (end of life)	1	1627	EMF-21	1627

*Composition of blend in refrigerated transport sector HFC-134a/R-404a/R-410a (61%/34.5%/0.05%)

**Composition of blend in refrigerated industrial sector HFC-134a/R-404a/R-407C (30%/59%/10%)

3.3.1.3 Mobile air conditioning

Emissions from mobile air conditioning have been in the centre of EU legislative attention due to the growing share of cars with air-conditioning and the high life-cycle emissions of mobile air conditioners. The European Commission (EC, 2003c) has proposed legislation to counterbalance this growth. Major emissions are caused by leakage and losses during the replacement of the refrigerant during the lifetime of the vehicle and at the end of the vehicle's life (Table 3.8).

Table 3.8: Calculation of HFC emissions from mobile air conditioning in GAINS

GAINS sectors	MAC Mobile air conditioning
Activity rate	Total sum of HFC refrigerants in vehicle stock and in scrapped vehicles
Unit	Ton of HFC
Data sources	RAINS databases on vehicle numbers; Oinonen and Soimakallio (2001); AEAT (2003) for the market share of air-conditioned cars

Table 3.9: Market shares of HFC-134a air-conditioners in new cars, their average charge and lifetime assumed in GAINS

	1995	2000	2005	2010	2015	2020	2025	2030
Fenno-Scandia	5 %	38 %	50 %	50 %	50 %	50 %	50 %	50 %
Rest of EU-25+ Switzerland	15 %	50 %	70 %	75 %	75 %	75 %	75 %	75 %
Russia and former USSR	0 %	5 %	15 %	50 %	50 %	50 %	50 %	50 %
Article 5 countries	0 %	5 %	15 %	50 %	50 %	50 %	50 %	50 %
Average charge size [kg]	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Equipment lifetime [years]	12	12	12	12	12	12	12	12

In the past, the share of air-conditioned cars was lower in Europe than in Japan and the United States (US). Currently, 50 to 75 percent of all new vehicles sold in Europe have air-conditioning, compared to almost 100 percent in the US and Japan. The current share is expected to sharply increase in Europe (Oinonen and Soimakallio, 2001; AEAT, 2003). Estimates on the future penetration of air-conditioned cars in Fennoscandia (Norway, Finland, Sweden and Denmark) are based on Oinonen and Soimakallio (2001). For the other EU countries, projections by AEAT (2003) for the UK have been used.

Uncertainties in these projections are high. Other estimates (e.g., EC, 2003; p. 6) suggest a share of air-condition in the vehicle stock of 70 percent in 2010 and 90 percent in 2020. For the non-EU 25 countries, the former USSR and the European countries under Article 5 in the Montreal protocol with a slower CFC- phase out schedule, the assumptions taken in the GAINS 1.0 implementation are presented in Table 3.9.

The total bank of refrigerant is calculated from the number of vehicles (total stock). The annual use of refrigerant is calculated using the average lifetime of vehicle and the total vehicle stock. The following equation is used for calculating the use of refrigerant in new vehicles:

$$Use_{year\_i} = \frac{1}{12} * \frac{0.67}{1000} * Penetration_{year\_i} * stock_{year\_i} \qquad \text{Equation 3.1}$$

With this approach, the use of HFC is calculated as a function of the number of light-duty vehicles (stock), the penetration of HFC-based air conditioners, the average charge of HFC per car (in tons/car), and the vehicle lifetime (12 years). The average charge of refrigerant in air conditioning system is assumed at 0.67 kg HFC-134a per vehicle. Estimates are based on the assumptions listed in Table 3.9. After the year 2000, car stock data are extracted from the RAINS database on light duty vehicles. 1995 vehicle stock data is based on ACEA data, and, if not available, on Auto Oil (EC, 1999) or EUROSTAT (2003).

Figure 3.5 depicts the assumed penetration of HFC air conditioners as fraction of the total vehicle stock in the GAINS 1.0 baseline projection. Data are derived from activity data of the

RAINS database and the key assumptions presented in Table 3.9. The function assumes that air condition systems are refilled in case of leakage and that the amount of HFC is the same at the end of the vehicle lifetime (i.e., after 12 years) as it was when the vehicle was new. An average charge of 0.67 kg HFC-134a per vehicle is assumed, as well as lifetime emissions for mobile air conditioning equipment of 10 percent of the banked amount per year and 100 percent at the end of life in the no-control case. Resulting emission factors are presented in Table 3.10.

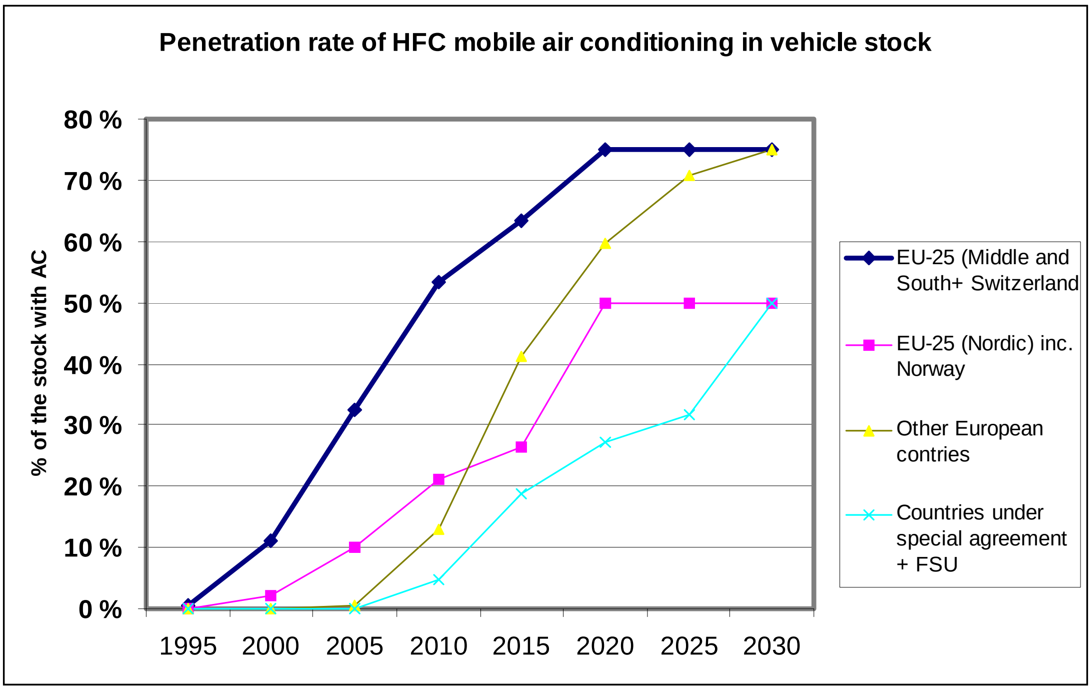

Figure 3.5: Penetration of HFC-134a based mobile air conditioning in Europe in light duty vehicles 1990-2030 (countries under special agreement are the Article 5 countries under the Montreal Protocol).

The German Federal Environment Agency (Schwarz 2001) has published a detailed study on the annual rate of emissions from passenger car air-conditioning systems in ‘up to seven years old’ vehicles. This report suggests average annual emissions of 8.2 percent of the charge for three different types of cars. Emission rates depend on the age of the vehicle. No indication of a linear loss rate in relation to the aging could be identified (Schwarz, 2001). A more recent study by Schwarz and Harnisch (2003) suggests a leakage rate of 6.9 percent per year and states that “climatic conditions seem not to influence much the leakage rate”. Other studies (Oinonen and Soimakallio, 2001) show significantly higher emissions (20 percent per year).

GAINS distinguishes two emissions from banking and from use through two sub-sectors (MAC_BANK, MAC_USE), with an average lifetime emission factor, assuming a vehicle lifetime of 12 years, of 1.914 ton CO_2eq per year. This is in line with estimates from the EC (2003c; p. 17), which suggest estimates of 1.7 to 2.34 ton per year.

Table 3.10: HFC emission factors for mobile air conditioning in GAINS

Sector	Abatement measure	Emission factor	GWP	Emission factor
		[t HFC-134/year/vehicle]		[t CO_2 eq./ year/activity]
MAC_B	No control	0.1	1300	130
MAC_S	No control	1	1300	1300

3.3.1.4 Aerosols

HFC emissions from aerosols are mainly released from aerosol propellant cans and metered dose inhalers that are used for medical purposes such as asthma inhalers. In these applications HFC is used as propellant so that it vaporises immediately. GAINS uses the amount of emissions itself as the activity, with HFC emissions in tons per year as activity units (Table 3.11). Emission estimates and activity forecasts are based on the national communications to the UNFCCC, as well as on Harnisch and Schwarz (2003), Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003) and Poulsen (2001). GAINS 1.0 assumes that the annual growth of aerosols using HFCs follows the average growth of the GDP.

Table 3.11: Calculation of HFC emissions from aerosol use in GAINS

GAINS sectors	AERO	Aerosol use		
Activity rate	HFC emissions as reported to UNFCCC			
Unit	HFC tons/year			
Data sources	Common reporting formats and National communications to UNFCCC; Harnisch and Schwarz (2003); Schwarz and Leisewitz (1999); Oinonen and Soimakallio (2001); AEAT (2003); Poulsen (2001)			
Emission factors				
Sector	Emission control	Emission factor [t HFC/t HFC emitted]	GWP	Emission factor [t CO_2eq./t HFC emitted]
AERO	No control	1.0	1,300	1,300

3.3.1.5 Polyurethane one component foam

The main application of polyurethane (PU) one component (OC) foam (Table 3.12) is to fill cavities and joints when installing inner fixtures in housing construction. Since OC foams come in pressurised canisters and cylinders, they are also called aerosol foams. One component blowing agents are typically gaseous, as they function as a blowing agent and as a propellant for the foam. They volatilise upon application, except for small residues that remain for at most one year in the hardened foam (Schwarz and Leisewitz, 1999).

Table 3.12: Calculation of HFC emissions from one component foam (OC) in GAINS

GAINS sectors	OC	Polyurethane one component foam		
Activity rate	HFC emissions from OC as reported to UNFCCC			
Unit	HFC tons/year			
Data sources	Common reporting formats and National Communications to UNFCCC; Harnisch and Schwarz (2003); Schwarz and Leisewitz (1999); Oinonen and Soimakallio (2001); AEAT (2003); Poulsen (2001)			
Emission factors				
Sector	Emission control	Emission factor [t HFC/t HFC used]	GWP	Emission factor [t CO_2eq./t HFC emitted]
OC	No control	1.0	1,300	1,300

Since there are country-specific variations in the composition of HFC blend inside the can, emissions (expressed in tons HFC/year) rather than can production are used as activity variables in GAINS. The full volume of HFC inside the can was assumed to vaporise immediately. Emission estimates and activity forecasts are based on the common reporting formats and the national communications to UNFCCC, as well as on Harnisch and Schwarz (2003), Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001) and AEAT (2003). GAINS 1.0 assumes that the annual growth of aerosols using HFC follows the average growth in GDP. The UNFCCC-CRF category used for activity data source was hard foam (more specifically HFC-134a and HFC-152a compounds) with a product emission factor of one.

3.3.1.6 Other foams

The other foams (OF) sector in GAINS (Table 3.13) includes about 10 different polyurethane foam types (PU appliances, PU/PIR/Phen laminates, PU disc panel, PU cont panel, PU blocks, PU spray, PU pipe, XPS) and extruded polystyrene (XPS). It is difficult to estimate product life emissions and lifetime of the foam product. End of life emissions depend greatly on the end of life treatment. If the product is landfilled, the emission factor depends greatly on the properties of the plastic. If the product is recycled, all gases can be emitted into the atmosphere if fugitive emissions during the recycling process are not incinerated or collected. If the product is incinerated, the emission factor can be close to zero, depending on the incineration temperature. GAINS uses emissions itself as the activity unit (HFC emissions ton/year). Emission estimates are based on the national communications to the UNFCCC.

The assumed growth for the whole sector is based on insights from more detailed studies (Schwarz and Leizewitz 1999; AEAT, 2003). These estimates take into account the assumed average market growth of this sector, the ratio between hydrocarbons and HFCs in foam cells, differences in product life times (15 to 50 years), as well as differences in production, lifetime and disposal emissions.

Table 3.13: Calculation of HFC emissions from other foams in GAINS

GAINS sectors	OF	Other polyurethane foams		
Activity rate	HFC emissions from other foams and XPS foam as reported to UNFCCC			
Unit	HFC tons/year			
Data sources	Common reporting formats and national communications to UNFCCC			
Sector	Emission control	Emission factor [t HFC/t HFC emitted]	GWP	Emission factor [t CO_2eq/t HFC used]
OF	No control	1.0	815	815

3.3.1.7 Other HFC emission sources

This sector (HFC_OTH) includes all other emission sources of HFC that are not described above (see Table 3-14). These include fire extinguishers, solvents, some air conditioning and refrigerator applications, HFC manufacturing emissions, and so forth. As activity variables for this sector, GAINS uses HFC emissions. Both past and future emissions of this sector are based on the national communications and projections to UNFCCC, as well as on Harnisch and Schwarz (2003), Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003), and Poulsen (2001).

Table 3.14: Calculation of HFC emissions from other HFC applications in GAINS

GAINS sectors	HFC_OTH	Other HFC applications		
Activity rate	HFC emissions from different applications ton/year			
Unit	HFC tons/year			
Data sources	Common reporting formats and national communications to UNFCCC			
Sector	Emission control	Emission factor [t HFC/t HFC reported]	GWP	Emission factor [t CO_2eq/t HFC used]
HFC_OTH	No control	1	1,300	1,300

3.3.2 Perfluorocarbon compounds (PFC) emissions

Two important sectors emit perfluorocarbon compounds (PFCs): primary aluminium production and the semiconductor industry. Emissions from these sectors have very high global warming potentials: tetrafluoromethane (CF_4) 6,500 and hexafluoroethane (C_2F_6) 9,200 times that of CO_2 for a 100-year time horizon.

3.3.2.1 Primary aluminium production

Primary aluminium production has been identified as a major anthropogenic source of emissions of two PFCs (CF_4 and C_2F_6). During normal operating conditions, an electrolytic cell used to produce aluminium does not generate measurable amounts of PFC. PFC is only produced during brief upset conditions known as "anode effects". These conditions occur when the level of aluminium oxide drops too low and the electrolytic bath itself begins to undergo electrolysis. Since the aluminium oxide level in the electrolytic bath cannot be directly measured, surrogates such as cell electrical resistance or voltage are most often used in modern facilities to ensure that the aluminium in the electrolytic bath is maintained at the correct level.

GAINS 1.0 uses the volume of aluminium production as the activity variable for calculating emissions from this source. Activity data are based on UN statistics and data on production technologies from the aluminium industry website (http://www.aluminium.net/smelters). They are, together with projections, already part of the existing RAINS database. Emission factors depend on the production technology (

Table 3.15) and on a number of site-specific conditions. The International Aluminium Institute (IAI, 2002) published lower emission factors than shown in the table, indicating that considerable variations exist between smelters using the same technology. That study covers all smelters in the EU-25, but does not provide site-specific or country-specific emission factors. Based on data from the aluminium industry website (http://www.aluminium.net/smelters) on the shares of the different aluminium production technologies in the European countries and the technology-specific emission factors presented in Table 3.15, country-specific emission factors are calculated for the use in GAINS (Table 3.16).

Table 3.15: Calculation of PFC emissions from aluminium production in GAINS

GAINS sectors	ALU_PFPB	Primary aluminium prod, point feeder prebake
	ALU_SWPB	Primary aluminium prod, side worked prebake
	ALU_VSS	Primary alum prod, vertical stud Söderberg
Activity rate	Primary aluminium production	
Unit	Ton primary aluminium produced per year	
Data sources	RAINS databases	
Emission factors		
Technology		Emission factor [kg CF_4eq/ton Al]
Point feeder prebake	PFPB	0.06
Centre worked prebake	CWPB	0.4
Side worked prebake	SWPB	1.9
Vertical stud Söderberg	VSS	0.7
Horizontal stud Söderberg	HSS	0.7

Source: Harnisch and Hendricks (2000)

For total aluminium production (PR_ALUM), GAINS distinguishes three different types of activities: ALU_PFPB, ALU_SWPB and ALU_VSS representing the technologies of point feeder prebake, side worked prebake, and vertical stud Söderberg, respectively.

Table 3.16: Percentages of different primary aluminium production technologies in Europe (only countries with primary aluminium production presented). Source: http://www.aluminium.net/smelters; Peek (2004). Acronyms for the technologies are given in Table 3.15.

	1995 PFPB	1995 SWPB	1995 CWPB	1995 VSS/HSS	2000 PFPB	2000 SWPB	2000 VSS/HSS
Bosnia-Herzegovina	0 %	0 %		0 %	100 %	0 %	0 %
France	79 %	21 %			79 %	21 %	
Germany	31 %	20 %	50		88 %	12 %	
Greece	100 %				100 %		
Hungary				100 %			100 %
Italy	100 %				100 %		
Netherlands	0 %	100 %			36 %	64 %	
Norway					50%		50 %
Poland					50 %		50 %
Romania					100%		
Russia (Karelia and Kola Peninsula)				100 %			100 %
Russia (remaining parts in Europe)							
Republic of Slovakia	100 %				100 %		
Slovenia	100 %				100 %		
Spain		55 %		45 %	54 %		45 %
Sweden	25 %			75 %	25 %		75 %
Switzerland	100 %				100 %		
Ukraine				100 %			100 %
Serbia Montenegro	100 %				100 %		
United Kingdom	96 %			4 %	96 %		4 %
Turkey				100 %			100 %

3.3.2.2 Semiconductor industry, PFC use in CVD and etching

The semiconductor industry uses HFC-23, CF_4, C_2F_6, octafluoropropane (C_3F_8), carbon tetrafluoride ($c\text{-}C_4F_8$), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) in two production processes: plasma etching thin films (etch) and plasma cleaning chemical vapour deposition (CVD) tool chambers (Table 3.17). Because PFC is only used by few companies in a country and because the amount of PFC use allows deriving production volumes, data on PFC use are often confidential.

GAINS uses as activity variables for this sector the volume of PFC emissions. Data are derived from national communications to the UNFCCC, from Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003) Poulsen (2001), and US EPA (2001b).

Table 3.17: Calculation of PFC emissions from semiconductor production in GAINS

GAINS sectors	SEMICOND	PFC use in semiconductor industry		
Activity rate	PFC emissions			
Unit	tons/year			
Data sources	National Communications to the UNFCCC; Schwarz and Leisewitz (1999); Oinonen and Soimakallio (2001); AEAT (2003); Poulsen (2001)			
Sector	Emission control	Emission factor [t PFC/t PFC reported]	GWP	Emission factor [t CO_2eq./t HFC used]
SEMICOND	No control	1	6,500	6,500

3.3.3 Sulphur hexafluoride (SF_6) emissions

Sulphur hexafluoride emissions arise from high and mid-voltage switches, magnesium production and casting and a variety of other applications using SF_6.

3.3.3.1 High and mid voltage switches

Sulphur hexafluoride is a manufactured gas used mainly as an electrical insulator in the transmission and distribution equipment of electric systems (Table 3.18). The use of SF_6 in electrical transmission and distribution equipment slowly increased between the 1970's and the mid-1990's, with new SF_6 equipment gradually replacing older oil and compressed air systems. Suitable alternatives to SF_6 do not exist for these applications as oil and compressed air systems suffer from safety and reliability problems (AEAT, 2003).

Most of the SF_6 is stored in gas-insulated switchgears for high and mid-voltage electric networks. Therefore, emissions of SF_6 depend on the age of the gas insulated switchgear (GIS) since older models leak more than newer ones, as well as on the size of the transmission network and recycling practices of "old" SF_6. Although specialised methods for the estimation of SF_6 emissions from electrical equipment have been developed (Schaefer *et al.*, 2002), implementation of these methods would need significant information on transmission network length and the age and size of utilities, which is not readily available at the European scale.

GAINS 1.0 uses as activity variables for this sector the amount of SF_6 emissions. Emission factors rates have been taken from the common reporting formats and national communications to the UNFCCC and other country reports from the German Federal Environmental Agency (Schwarz and Leisewitz, 1999), VTT Energy in Finland (Oinonen and Soimakallio, 2001), AEAT (AEAT, 2003), and Poulsen (2001). When countries did not report their emissions, estimates from USEPA (USEPA, 2001b) have been used. It is important to note that in some Eastern European countries other insulation gases/methods are still used (see the 3rd National communication of Latvia to the UNFCCC and Kokorin and Nakuthin, 2000).

Table 3.18: Calculation of SF_6 emissions from high and mid-voltage switches in GAINS

GAINS sectors	GIS	SF_6 use in high and mid voltage switches		
Activity rate	SF_6 emission from switches			
Unit	tons/year			
Data sources	Common reporting formats and National Communications to the UNFCCC; Schwarz and Leisewitz (1999); Oinonen and Soimakallio (2001); AEAT (2003); Poulsen (2001)			
Sector	Emission control	Emission factor [t SF_6/t SF_6 reported]	GWP	Emission factor [t CO_2eq./t SF_6 used]
GIS	No control	1	23,900	23,900

3.3.3.2 Magnesium production and magnesium casting

Casting and production of primary and secondary magnesium (Table 3.19) are well known sources of atmospheric emissions of SF_6. Sulphur hexafluoride is used as a shielding gas in magnesium foundries to protect the molten magnesium from re-oxidizing whilst it is running to best casting ingots. Activity data on historic volumes of processed magnesium are taken from the World Mineral Statistics (Taylor *et al.*, 2003), UN statistics and the national communications to UNFCCC. Use of SF_6 in these processes is assumed to remain stable.

The emission factor of 1 kg SF_6/ton of processed metal is based on the average emission factors published in Schwarz and Leisewitz (1999) and Oinonen and Soimakallio (2001).

Table 3.19: Calculation of SF_6 emissions from magnesium production and casting in GAINS

GAINS sectors	MAGNPR	Magnesium production and casting		
Activity rate	Magnesium processed			
Unit	tons/year			
Data sources	National Communications to the UNFCCC; Schwarz and Leisewitz (1999); Oinonen and Soimakallio (2001); AEAT (2003); Poulsen (2001)			
Sector	Emission control	Emission factor [kg SF_6/t magnesium processed]	GWP	Emission factor [t CO_2eq./t SF6 used]
MAGNPR	No control	1	23,900	23,9

3.3.3.3 Other sources of sulphur hexafluoride (SF_6) emissions

Some European countries used significant amounts of SF_6 in tires and soundproof windows. Some countries also use SF_6 in the semiconductor industry. Some sport equipment manufacturers use SF_6 in tennis balls and sport shoes, but this use is relatively small and emissions are hard to forecast. For the latter, the industry in question has agreed to reduce the use of SF_6 over time (Harnisch and Schwarz, 2003; p. 23). GAINS uses as activity variables for this sector the amount of SF_6 emissions as reported by countries to UNFCCC. Emissions from these other sources are taken from common reporting formats (CRF) and national communications to the UNFCCC or from other national reports (Schwarz and Leisewitz, 1999; Oinonen and Soimakallio, 2001; AEAT, 2003; Poulsen, 2001).

The category “Other sources” distinguishes two sub-sectors, i.e., windows (WIND_B) and other SF_6 emissions (SF6_OTH) – see Table 3.20. In some countries, use of SF_6 in soundproof windows can lead to significant end of life emissions in the future.

Table 3.20: Calculation of SF_6 emissions from other SF_6 sources in GAINS

GAINS sectors	SF6_OTH	Other sources of SF_6 emissions		
	WIND_B	Soundproof windows		
Activity rate	Reported emissions of SF6			
Unit	Tons/year			
Data sources	Common reporting formats and national communications to the UNFCCC; Harnisch and Schwarz (2003); Schwarz and Leisewitz (1999); Oinonen and Soimakallio (2001); AEAT (2003); Poulsen (2001)			
Sector	Emission control	Emission factor [t SF_6/t emitted]	GWP	Emission factor [t CO_2eq/t SF_6]
WIND_B		1	23,900	23,900
SF_6_OTH	No control	1	23,900	23,900

4 Emission control options and costs

The GAINS model distinguishes several abatement options to reduce F-gas emissions from anthropogenic sources. Their removal efficiencies, costs and application potentials were determined based on the available literature data.

GAINS 1.0 includes only mitigation measures with proven technical feasibility, but does not (yet) consider new techniques that could become available in the future. Since most of the mitigation options for F-gases require modifications of the production processes, GAINS 1.0 assumes that such measures will only be applied to new built equipment (i.e., excluding retrofits of existing infrastructure). Consequently, application potentials in a given year reflect the natural turnover of the existing capital stock. Actual potentials are determined based on the assumption that implementation could start in 2004, except for mobile air conditioning, for which implementation is assumed to begin in 2007. Thus, depending on the technical lifetime of the equipment, the maximum application potentials in 2010 and 2015 will be restricted reflecting the turnover of the current stock of equipment. If a country has already implemented measures, the current degree of implementation is taken into account in the "current legislation" (CLE) scenario, and the remaining potential for additional measures (on top of the implementation required by the existing legislation) is calculated accordingly.

4.1 Options and costs of controlling HFC emissions

Table 4.1 summarizes the mitigation options for hydrofluorocarbons (HFC) emissions considered in GAINS 1.0. Removal efficiencies, the maximum technical application potential of the options are presented in Table 4.2.

Thermal oxidation, i.e., the process of oxidizing HFC-23 to carbon dioxide, hydrogen fluoride (HF) and water, is a demonstrated technology for the destruction of halogenated organic compounds. "*Good practice*" reflects a package of measures including improved components, leak prevention (maintenance) and end of life recollection of the refrigerant. "*Process modification"* includes changes of the process type from ordinary to secondary loop systems, and in some cases alternative refrigerants. Secondary loop systems pump cold brine solutions through a second set of loops away from the refrigeration equipment and into areas to be cooled. These systems require a significantly lower refrigerant charge, have lower leak rates, and allow the use of flammable or toxic refrigerants. The primary disadvantage of the secondary loop system is a loss of energy efficiency (US EPA, 2001a).

GAINS 1.0 considers the use of ammonia and hydrocarbons as alternative refrigerants for stationary cooling and stationary air conditioning systems. For mobile air conditioning and refrigerated transport, the major alternative refrigerant is pressurized CO_2. For one component foam, using an alternative blowing agent would mean changing R-134a partly to R-152a or to hydrocarbons. In the foams sector, CO_2 is an alternative for extruded polystyrene (XPS). For mobile air conditioning closed CO_2 systems are possible, although not yet commercially available. Refrigerated transport uses open CO_2 systems, which are refilled after every journey, which is a commercially viable technique. Costs of the HFC mitigation options are presented in Table 4.3.

Table 4.1: Mitigation options for HFC emissions considered in GAINS

Emission source	GAINS sector	Technology description	GAINS acronym
HCFC-22 production	HCFC22	Incineration: post combustion of HFC-23 emitted from production of HCFC-22	INC
Industrial refrigeration (bank)	IND_B	Good practice: leakage control, improved components	GP_INDB
	IND_B	Process modifications including alternative refrigerants	PM_INDB
Industrial refrigeration (scrap)	IND_S	Good practice: end-of-life recollection	GP_INDS
	IND_S	Process modifications including alternative refrigerants	PM_INDS
Commercial refrigeration (bank)	COMM_B	Good practice: leakage control, improved components	GP_COMMB
	COMM_B	Process modifications including alternative refrigerants	PM_COMMB
Commercial refrigeration (scrap)	COMM_S	Good practice: end-of-life recollection	GP_COMMS
	COMM_S	Process modifications including alternative refrigerants	PM_COMMS
Domestic hermetic refrigerators (scrap)	DOM_S	Good practice: end-of-life recollection	GP_DOMS
Transport refrigeration (bank)	TRA_REFB	Alternative refrigerant: use of open CO2 refrigerant system	ALT_TRAB
	TRA_REFB	Good practice: leakage control, improved components	GP_TRAB
Transport refrigeration (scrap)	TRA_REFS	Alternative refrigerant: use of open CO2 refrigerant system	ALT_TRAS
	TRA_REFS	Good practice: end-of-life recollection	GP_TRAS
Stationary air conditioning (bank)	AIRCON_B	Good practice: leakage control, improved components	GP_STATB
	AIRCON_B	Process modifications including alternative refrigerants	PM_STATB
Stationary air conditioning (scrap)	AIRCON_S	Good practice: end-of-life recollection	GP_STATS
	AIRCON_S	Process modifications including alternative refrigerants	PM_STATS
Mobile air conditioning (bank)	MAC_B	Alternative refrigerant: HFC134a replaced by pressurized CO2	ALT_MACB
	MAC_B	Good practice: leakage control, improved components	GP_MACB
Mobile air conditioning (scrap)	MAC_S	Alternative refrigerant: HFC134a replaced by pressurized CO2	ALT_MACS
	MAC_S	Good practice: end-of-life recollection	GP_MACS
One component foam	OC	Alternative blowing agent: many different kinds	ALT_OC
Other foams	OF	Alternative blowing agent: many different kinds	ALT_OF
Aerosols	AERO	Alternative propellant	ALT_PROP

Table 4.2: Mitigation options for HFC emissions, their emission removal efficiencies and the maximum technical application potential considered in GAINS 1.0

GAINS sector acronym	GAINS technology acronym	Emission removal efficiency	Maximum application potential
HCFC22	INC	95 %	100 %
IND_B	GP_INDB	42 %	100 %
IND_B	PM_INDB	100 %	Increasing from 7 % in 2005 to 80 % in 2030
IND_S	GP_INDS	88 %	100 %
IND_S	PM_INDS	100 %	Increasing from 7 % in 2020 to 67 % in 2030
COMM_B	GP_COMMB	33 %	100%
COMM_B	PM_COMMB	100 %	Increasing from 10 % in 2005 to 80 % in 2030
COMM_S	GP_COMMS	80 %	100 %
COMM_S	PM_COMMS	100 %	Increasing from 10 % in 2015 to 80 % in 2030
TRA_REFB	GP_TRAB	80 %	100 %
TRA_REFB	ALT_TRAB	100 %	Increasing from 7 % in 2010 to 50 % in 2030
TRA_REFS	GP_TRAS	20 %	100 %
TRA_REFS	ALT_TRAS	100 %	Increasing from 7 % in 2005 to 50 % in 2030
AIRCON_B	PM_STATB	100 %	Increasing from 7 % in 2015 to 100 % in 2030
AIRCON_B	GP_STATB	30 %	100 %
AIRCON_S	PM_STATS	100 %	Increasing from 7 % in 2020 to 67 % in 2030
AIRCON_S	GP_STATS	88 %	100 %
DOM_S	GP_DOMS	80 %	100 %
MAC_B	ALT_MACB	100 %	Increasing from 33 % in 2010 to 100 % in 2030
MAC_B	GP_MACB	50 %	100%
MAC_S	ALT_MACS	100 %	Increasing from 33 % in 2020 to 100 % in 2030
MAC_S	GP_MACS	80 %	100 %
OC	ALT_OC	85 %	100 %
OF	ALT_OF	100 %	Increasing from 2 % in 2015 to 52 % in 2030
AERO	ALT_PROP	100 %	8 %

Table 4.3: Costs of HFC mitigation options

Sector acronym	Technology acronym	Lifetime of equipment [years]	Investments [€/activity]	Electricity use [% increase]	Fixed O&M costs [€/activity/year]	Variable O&M costs [€/activity/year]	Average abatement cost [€/t HFC]	Average abatement cost [€/t CO_2eq.]
HCFC22	INC	10	15,000	0	2,000	0	4,052	0.35
IND_B	GP_INDB	15	3,333	0	5000	0	39,266	15.1
IND_B	PM_INDB	15	51,192	3	3000	4163	55,383	21.3
IND_S	GP_INDS	15	3,333	0	5000	0	39,266	15.1
IND_S	PM_INDS	15	51,192	3	3000	4163	55,383	21.3
COMM_B	GP_COMMB	10	10,000	0	5000	0	49,503	18.1
COMM_B	PM_COMMB	10	100,000	15	3000	2250	67,016	24.6
COMM_S	GP_COMMS	10	10,000	0	5000	0	49,503	18.1
COMM_S	PM_COMMS	10	100,000	15	3000	2250	67,016	24.6
TRA_REFB	ALT_TRAB	15	0	0	1719	0	4,000	2.0
TRA_REFB	GP_TRAB	15	12,500	0	5000	0	35,632	17.8
TRA_REFS	ALT_TRAS	15	0	0	1719	0	4,000	2.0
TRA_REFS	GP_TRAS	15	12,500	0	5000	0	35,632	17.8
AIRCON_B	GP_STATB	20	8,333	0	3000	0	63,302	38.9
AIRCON_B	PM_STATB	20	80,000	20	3000	4000	81,054	49.8
AIRCON_S	GP_STATS	20	8,333	0	3000	0	63,302	38.9
AIRCON_S	PM_STATS	20	80,000	20	3000	4000	81,054	49.8
DOM_S*	Alternatives	15	166,667	0	0	0		
DOM_S	GP_DOMS	15	150,000	0	0	0	19,026	14.6
MAC_B	ALT_MACB	12	50	0	0	0	33,264	25.6
MAC_B	GP_MACB	12	10	0	1.24	0	29,516	22.7

Table 4.3 (continued): Costs of HFC mitigation options

Sector acronym	Technology acronym	Lifetime of equipment [years]	Investments [€/activity]	Electricity use [% increase]	Fixed O&M costs [€/activity/year]	Variable O&M costs [€/activity/year]	Average abatement cost [€/t HFC]	Average abatement cost [€/t CO_2eq.]
MAC_S	ALT_MACS	12	50	0	0	0	33,264	25.6
MAC_S	GP_MACS	12	10	0	1.24	0	29,516	22.7
OC	ALT_OC			0	0.4	0	650	0.5
OF	ALT_OF			0	4.9	0	6,370	4.9
AERO	ALT_PROP						1,300	1.0

*For the domestic sector, costs are presented per ton of HFC used

Sources: Devotta *et al.* (2004); Harnisch and Schwarz (2001); Harnisch and Hendriks (2000); Heijnes *et al.* (1999); Jyrkonen (2004), US EPA (2001a); Oinonen and Soimakallio (2001); Pedersen (1998); Kaapola (1989)

As described in Section 3.3, GAINS 1.0 distinguishes for each of the sectors IND, COMM, TRA_REF, AIRCON and MAC (Table 3.3) two elements, i.e., emissions from banks and emissions from scrapping at the end of life. Cost data in GAINS (per ton CO_2eq) include costs of both elements.

If significant discrepancies between costs estimates from different sources have been detected, most recent data were used for GAINS 1.0. For the preliminary cost estimates of GAINS 1.0, an average cost for energy of 5 cents per kWh has been assumed. The calculation of the average use of energy per ton of HFC in conventional systems assumes the utilization period of maximum loads described in Kaapola (2001) and Pedersen (1998), see Table 4.4. Indirect emissions resulting from extra energy consumption have been ignored in the emissions and cost calculations.

Table 4.4: Assumptions for average electricity use per ton of HFC in GAINS

Sector	Average electricity use per MWh/t_{HFC}
COMM	2000
IND	2300
AIRCON	430*

*Stationary air conditioning have significant differences depending on climate

4.2 Options and costs of controlling PFC emissions

4.2.1 Primary aluminium production

Table 4.5 lists the mitigation measures for perfluorocarbon compound (PFC) emissions in the primary aluminium production sector considered in GAINS 1.0. Removal efficiencies and application potentials of these options are listed in Table 4.6.

Table 4.5: Mitigation options for controlling PFC emissions considered in GAINS

Emission source	GAINS sector	Technology description	GAINS technology acronym
Primary aluminium production	ALU_SWPB	SWPB to PFPB conversion	CONVSWPB
	ALU_SWPB	SWPB retrofitting	RETSWPB
	ALU_VSS	VSS to PFPB conversion	CONVVSS
	ALU_VSS	VSS retrofitting	RETVSS

Table 4.6: Removal efficiencies and maximum application potentials for conversion and retrofitting of aluminium smelters

GAINS sector	GAINS technology acronym	Emission removal efficiency	Application potential
ALU_VSS	CONVVSS	92 %	100%
ALU_VSS	RETVSS	26 %	100%
ALU_SWPB	CONVSWPB	97 %	100%
ALU_SWPB	RETSWPB	26 %	100%

Table 4.7 presents the economic features of the mitigation measures. The reduction of the frequency and duration of anode effects has double benefits by reducing PFC emissions and optimising process efficiency. Investments are given per unit of installed production capacity. Different literature sources indicate large variations in investment costs, where the lower cost estimates lead to negative mitigation costs (e.g., net benefits). It is assumed that process improvements with negative costs have already been implemented in the base year due to their economic benefits. For the remaining plants where such improvements have not yet been implemented, the higher cost estimates presented in the literature are assumed as representative. Thus, in practice GAINS 1.0 applies investment data from Harnisch *et al.* (1998), O&M costs are based on Harnisch and Hendricks (2000) (Table 4.7). For smelters, an average lifetime after improvement of 20 years has been assumed.

Table 4.7: Costs for conversion and retrofitting of smelters (Harnisch *et al.*, 1995; Harnisch and Hendriks, 2000).

GAINS sector	GAINS technology	Lifetime of equipment [years]	Investments [€/t aluminium production capacity]	Variable O&M costs [€/t alum./year]	Average costs [€/t PFC]	Average costs [€/t CO_2eq]
ALU_VSS	CONVVSS	20	2,200	0	255,243	39.3
ALU_VSS	RETVSS	20	250	-10	46,129	7.1
ALU_SWPB	CONVSWPB	20	5300	-75	18,253	2.8
ALU_SWPB	RETSWPB	20	592	0*	8,818	1.4

*While retrofitting improves process, GAINS 1.0 assumes transaction costs of 20 €/activity

4.2.2 Semiconductor manufacture

Use of nitrogen trifluoride (NF_3) instead of PFC is the only mitigation option identified for the reduction of PFC emissions from the semiconductor sector (Table 4.8). Removal efficiency, application potential and costs are presented in Table 4.9. In the absence of detailed activity data for PFC use in the semiconductor industry, it is assumed that limiting PFC use and increasing NF_3 use could lead to a 99 percent reduction of PFC emissions in chemical vapour deposition (CVD) chambers compared to baseline in 2010. It is also assumed that CVD chamber cleaning use covers approximately 60 percent of total PFC use/emissions in year 2010 (Harnisch and Hendriks, 2000). This is in agreement with the process line age structure estimates reported in Harnisch *et al*. (2000). The European semiconductor manufacturers have committed themselves to a 10 percent reduction relative to the 1995 base year.

Additional investments for NF_3 use amount to 70,000 €/chamber (Harnisch *et al*., 2000), resulting in average annual costs between 156,000 and 169,000 €/ton CF_4 used (Harnisch and Hendriks, 2000; Oinonen and Soimakallio, 2001). The application potential is estimated to cover the total CVD part of this sector (maximum technical applicability in semiconductor sector 60 percent). Costs of 169,000 €/ ton of CF_4 is used in GAINS 1.0.

Table 4.8: Mitigation options for PFC emissions in the semiconductor sector considered in GAINS

Emission source	GAINS sector	Technology description	GAINS technology
Semiconductor manufacture	SEMICOND	Alternative solvent: use of NF3	ALT_SOLV

Table 4.9: Costs for the mitigation option for the semiconductor sector

GAINS sector	GAINS technology acronym	Removal efficiency	Application potential	Average costs [€/t PFC]	Average costs [€/t CO_2eq]
SEMICOND	ALT_SOLV	99 %	100 %	169,000	26.0

4.3 Options and costs of controlling SF_6 emissions

GAINS 1.0 considers four options for reducing SF_6 emissions: Good practice, use of SO_2 as an alternative protection gas, and bans of SF_6 for windows and other applications (Table 4.10).

Good practice for high and mid-voltage switchgears (GIS) includes leakage reduction and recycling of recollected SF_6 from end of life switchgears. Alternatives for magnesium production and casting means involves a change from SF_6 to sulphur dioxide (SO_2), and alternatives in sector “SF_6 other” means a phase-out of SF_6 for tires and sound proof windows.

Table 4.10: Mitigation options for controlling SF_6 emissions considered in GAINS

Emission source	GAINS sector	Technology description	GAINS technology acronym
High and mid voltage switches	GIS	Good practice: leakage control and end-of-life recollection and recycling	GP_GIS
Magnesium produc. and casting	MAGNPR	Alternative protection gas: SF6 replaced by SO2	ALT_MAGN
Windows	WIND_B	Ban of use	ALT_WIND
SF_6 other	SF6_OTH	Ban of use	ALT_SF

Removal efficiencies, application rates and abatement costs for the control options are presented in Table 4.11. Cost data are based on Harnisch and Hendriks (2000), Oinonen and Soimakallio (2001), and Harnisch and Schwarz (2003). Average costs of good practice measures (leakage reduction, regular checking routines of switches and end of life recollection of SF_6) are estimated at 19,000 €/t SF_6 abated. Changing SF_6 to SO_2 is estimated to cost on average 7,170 €/t SF_6 abated. Average cost for replacing SF_6 use in magnesium production and casting is 12.5 €/t SF_6. The literature presents negative costs for alternatives for tires and soundproof windows (Harnisch and Schwarz, 2003). To represent potential transaction costs, 2,390 €/t SF_6 (0.1 €/t CO_2eq.) are assumed in GAINS 1.0.

Table 4.11: Removal efficiencies, application potentials and costs of the SF_6 mitigation options

GAINS sector	GAINS technology acronym	Removal efficiency	Application potential	Average costs [€/t SF_6]	Average costs [€/t CO_2eq]
GIS	GP_GIS	84 %	100 %	86,040	3.6
MAGNPR	ALT_MAGN	100 %	100 %	2,390	0.1
WIND_B	ALT_WIND	100 %	Increasing from 20 % in 2010 to 100 % in 2030	2,390	0.1
SF6_OTH	ALT_SF	100 %	100 %	2,390	0.1

*The application potential depends on the "stored" SF_6 in windows and tennis balls. For GAINS 1.0 it is assumed that this stock will have disappeared in 2020. Use of SF_6 in semiconductor manufacturing is relatively small and does not affect future emission.

5 Interactions with other pollutants

There exist a number of direct interactions between activities that emit fluorinated gases and other pollutants (Table 5.1). The use of alternative refrigerants may lead to an increased electricity use in some sectors (COMM, IND and AIRCO). Regarding hydrofluorocarbons (HFC) emissions, mobile air conditioning not only increases HFC emissions but it also increase fuel consumption thereby increasing other emissions. Primary aluminium production is also a source of particulate matter (PM) emissions, and changing the technology will affect PM emissions (Klimont *et al.*, 2002). Abatement options that affect perfluorocarbon compound (PFC) emissions also affect carbon dioxide (CO_2) (Houghton *et al.*, 1997). For example, the infrastructure of an electricity distributing network depends also on the structure of a country's energy conversion system. This affects the amount and size of gas insulated switchgears.

Table 5.1: Interactions between fluorinated gases and other greenhouse gases and traditional air pollutants

Emissions		CO_2	SO_2	NO_x	PM	
HFC	Refrigeration & SAC	x	x	x	x	Increased electricity use
	Mobile Air Conditioning (MAC)	x		x	x	Increased fuel use
	Foam	x				Change in insulation properties
PFC	Primary Aluminium production	x	x	x	x	Decrease through process improvement
SF6	Switches	x	x	x	x	Infrastructure of network

6 Results

6.1 Historic emissions

6.1.1 Emission estimates for the base year

GAINS estimates for 1995 for the entire GAINS 1.0 model domain are presented in Table 6.1 with sector contributions displayed in Figure 6.1. Country-specific data have been collected for the most important sectors where activity data are available, i.e., for HCFC-22 production, primary aluminum production and magnesium production. However, very little is known about hydrofluorocarbon (HFC) use in non-EU countries. Therefore, estimates for these countries are more uncertain. Exceptions are the production of difluorochloromethane (HCFC-22) and primary aluminium, for which data availability is generally good.

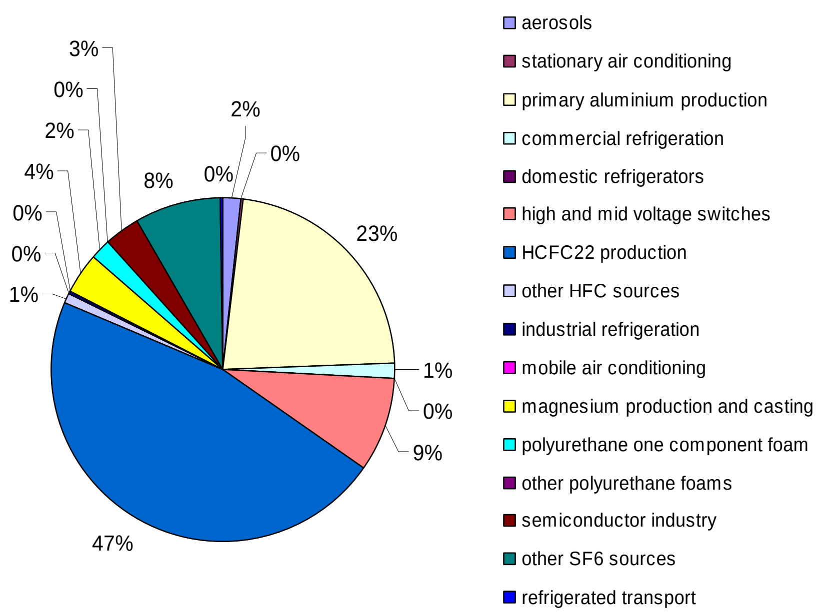

Figure 6.1: F-gas emissions 1995 by sector for GAINS 1.0 model domain. Total emissions: 87 Mton CO_2eq.

6.1.2 Comparison with other estimates

The GAINS estimates for 1995 are compared with the national submissions to the United Nations Framework Convention on Climate Change (UNFCCC) and estimates provided by ECOFYS in Table 6.2. To the extent that national data are available and comparable, the GAINS estimates show reasonable agreement, although in some cases major discrepancies do occur. These can be chiefly traced back to differences in HCFC-22 activity data and emission factors, especially for those sectors that use F-gases with high global warming potential (GWP) such as GIS and primary aluminium production.

Table 6.1: GAINS estimates of F-gas emissions in 1995 (Mt CO_2eq.)

Country	HFC	PFC	SF_6	SUM
Albania	0.0	0.0	0.0	0.0
Austria	0.5	0.0	1.2	1.7
Belarus	0.0	0.0	0.0	0.0
Belgium	0.0	0.0	0.4	0.4
Bosnia-H	0.0	0.0	0.0	0.1
Bulgaria	0.0	0.0	0.0	0.0
Croatia	0.0	0.0	0.0	0.0
Cyprus	0.0	0.0	0.0	0.0
Czech Republic	0.0	0.0	0.0	0.0
Denmark	0.2	0.0	0.1	0.3
Estonia	0.0	0.0	0.0	0.0
Finland	0.0	0.0	0.0	0.1
France	3.8	2.7	2.2	8.7
Germany	8.5	5.7	5.8	20.0
Greece	0.7	0.1	0.0	0.7
Hungary	0.0	0.1	0.0	0.1
Ireland	0.1	0.0	0.0	0.1
Italy	3.1	0.2	0.5	3.8
Latvia	0.0	0.0	0.0	0.0
Lithuania	0.0	0.0	0.0	0.0
Luxembourg	0.0	0.0	0.0	0.0
Macedonia	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0
Moldova	0.0	0.0	0.0	0.0
Netherlands	5.1	1.8	0.2	7.1
Norway	0.2	2.1	0.7	3.0
Poland	0.0	0.1	0.0	0.2
Portugal	0.1	0.0	0.0	0.1
Romania	0.0	0.0	0.0	0.0
Russia-Kaliningrad	0.0	0.0	0.0	0.0
Russia-Kola/Karelia	0.0	0.1	0.1	0.2
Russia-St Petersburg	0.0	0.0	0.1	0.1
Russia-Remaining Europe	11.7	4.9	3.9	20.5
Serbia-M	0.0	0.0	0.0	0.0
Slovakia	0.0	0.0	0.0	0.1
Slovenia	0.0	0.0	0.0	0.0
Spain	4.0	3.2	0.1	7.4
Sweden	0.0	0.3	0.2	0.5
Switzerland	0.0	0.0	0.0	0.0
Turkey	0.0	0.3	0.0	0.3
Ukraine	0.0	0.4	0.9	1.4
United Kingdom	8.2	0.3	0.9	9.4
Europe	46.3	22.6	17.9	86.7
Thereof: EU-25	34.4	14.6	11.9	60.9

Table 6.2: Comparison of GAINS 1.0 estimates of HFC, PFC and SF_6 emissions in 1995 with other emission inventories (Mt CO_2eq)

Country	HFC			PFC			SF_6		
	GAINS	UNFCCC	ECOFYS	GAINS	UNFCCC	ECOFYS	GAINS	UNFCCC	ECOFYS
Albania	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Austria	0.5	0.5	0.5	0	0	0.1	1.2	1.2	0.1
Belarus	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Belgium	0	0.3	0.6	0	n.a.	0	0.4	0.2	0
Bosnia-Herc.	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Bulgaria	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Croatia	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Cyprus	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Czech Rep.	0	0	n.a.	0	n.a.	n.a.	0	0.2	n.a.
Denmark	0.2	0.2	n.a.	0	0	0	0.1	0.1	0
Estonia	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Finland	0	0	0.3	0	0	0	0.0	0	0
France	3.8	1.3	7.3	2.7	1.3	1.5	2.2	2.3	1.9
Germany	8.5	6.4	14.2	5.7	1.8	1.5	5.8	6.2	1.4
Greece	0.7	3.4	0.9	0.1	0.1	0	0	0	0
Hungary	0	n.a.	n.a.	0.1	n.a.	n.a.	0	n.a.	n.a.
Ireland	0.1	0	0.2	0	0.1	0	0	0.1	0
Italy	3.1	0.7	6.9	0.2	0.3	0.2	0.5	0.5	0.5
Latvia	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Lithuania	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Luxembourg	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Macedonia	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Malta	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Moldova	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Netherlands	5.1	6	6.3	1.8	1.9	2.2	0.2	0.4	0.2
Norway	0.2	n.a.	n.a.	2.1	n.a.	n.a.	0.7	n.a.	n.a.
Poland	0	0	n.a.	0.1	0.8	n.a.	0	0	n.a.

Table 6.2 (continued): Comparison of GAINS 1.0 estimates of HFC, PFC and SF_6 emissions in 1995 with other emission inventories (Mt CO_2eq)

	HFC			PFC			SF_6		
	GAINS	UNFCCC	ECOFYS	GAINS	UNFCCC	ECOFYS	GAINS	UNFCCC	ECOFYS
Portugal	0.1	0	0.3	0	0.2	0	0	0	0
Romania	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Russia-	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Russia-	0	n.a.	n.a.	0.1	n.a.	n.a.	0.1	n.a.	n.a.
Russia-St	0	n.a.	n.a.	0	n.a.	n.a.	0.1	n.a.	n.a.
Russia-Remain.	11.7	n.a.	n.a.	4.9	n.a.	n.a.	3.9	n.a.	n.a.
Serbia-	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Slovakia	0	0	n.a.	0	0.1	n.a.	0	0	n.a.
Slovenia	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Spain	4.0	4.6	5.4	3.2	0.8	n.a.	0.1	0.1	0.2
Sweden	0	0.1	0.5	0.3	0.4	0.5	0.2	0.1	0.2
Switzerland	0	n.a.	n.a.	0	n.a.	n.a.	0	n.a.	n.a.
Turkey	0	n.a.	n.a.	0.3	n.a.	n.a.	0	n.a.	n.a.
Ukraine	0	n.a.	n.a.	0.4	n.a.	n.a.	0.9	n.a.	n.a.
UK	8.2	15.2	8.9	0.3	1.1	0.7	0.9	1.1	1
Total 42 regions	46.3	n.a.	n.a.	22.6	n.a.	n.a.	17.9	n.a.	n.a.
EU-15	34.4	38.7	52.3	14.6	8.0	n.a.	11.9	12.3	5.5

Source: UNFCCC national submissions (http://unfccc.int), Blok *et al.* (2001)

6.2 Projections of future emissions

6.2.1 Assumptions for the baseline projection

The GAINS 1.0 baseline estimate of future F-gas emissions relies for the 25 EU Member States on the projected activity levels of the baseline scenario of the "Energy Outlook" developed in 2003 by the Directorate General for Energy and Transport of the European Commission (Mantzos *et al*., 2003). As one basic assumption, this economic projection does not include any climate policy measures beyond those which were already in force in 2003. For the non-EU countries, national reports of activity projections have been used. Details on projected fuel consumption and production levels are available from the RAINS website (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/).

For projections of future F-gas emissions, it is important to reflect autonomous technological improvements for new investments that lead to lower F-gas emissions even in the absence of targeted greenhouse gas reduction strategies, while assuming frozen technology for existing installations. Assumed autonomous developments include for example good practise in GIS handling and banning certain SF_6 products or similar measures, which have small or even negative net abatement costs. For windows and foam use, emission forecasts from special reports (i.e., AEAT, 2003; Schwarz and Leisewitz, 1999) are used. The GAINS 1.0 baseline projection includes the expected impacts of the end of life collection of HFC refrigerants obligated by Directive 2000/53/EC on end-of-life vehicles (EU, 2002) and the Directive 2002/96/EC on waste from electric and electronic equipment (EU, 2003). These directives will reduce emissions, as they will require the extraction and proper disposal of HFCs in mobile air conditioning refrigerators and air conditioning units.

On the other hand, the "current legislation" (CLE) projection excludes proposals for national or EU-wide legislation on control of greenhouse gases, which are not yet agreed upon (such as the F-gas regulation proposed by the European Commission).

European semiconductor manufacturers have committed themselves to a 10 percent reduction relative to the 1995 base year. This results from the voluntary agreement of the World Semiconductor Council, which covers 90 percent of the global production of semiconductors (USDOS, 1999). As this voluntary agreement is not a legal obligation, it has not been taken into account for the GAINS 1.0 baseline projection.

While in some countries the end of life recollection of HFCs is already applied in some sectors due to Regulation (EC) No 2037/2000 of the European Parliament and the Council on substances that deplete the ozone layer (29. 6. 2000), it has not been taken into account in the GAINS 1.0 baseline projection.

6.2.2 The current legislation baseline projection for 2020

With the assumptions outlined above, overall emissions of F-gases in the GAINS 1.0 model domain are computed to increase in terms of their CO_2 equivalents by more than 140 percent between 1995 and 2020 (Table 6.3). This growth is mainly caused by the increase in HFC emissions (+250 percent) from different types of refrigeration and air conditioning. The HFC increase is a combined effect of replacing the use of CFCs with HFCs in accordance with the Montreal Protocol and an expected increase in demand for refrigeration and air conditioning. A more limited growth is expected in PFC emissions (+60 percent), while SF_6 emissions are expected to decline by 30 percent. Thus, the contribution of HFC to total F-gas emissions will grow from 53 percent in 1995 to 77 percent in 2020.

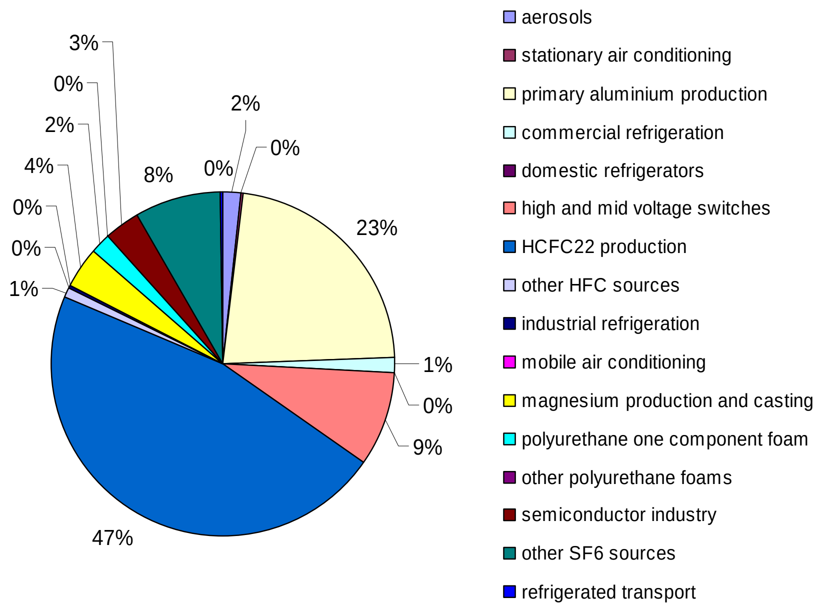

Figure 6.2: Sectoral development of F-gas emissions 1995-2030 for the GAINS model domain in the current legislation (CLE) scenario.

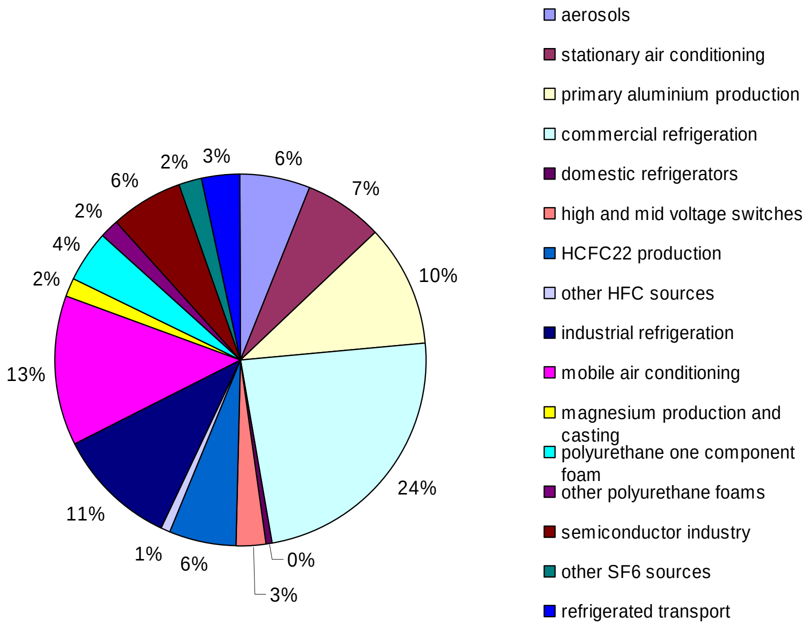

Figure 6.3: F-gas emissions in 2020 by sector for GAINS 1.0 model domain in the current legislation scenario. Total emissions: 212 Mton CO_2eq.

Table 6.3: The current legislation baseline projection of HFC, PFC and SF_6 emissions for 2020 (Mt CO_2eq)

	HFCs	PFCs	SF_6	SUM
Albania	0.1	0.0	0.0	0.2
Austria	3.7	0.0	0.6	4.3
Belarus	1.4	0.0	0.0	1.4
Belgium	3.1	0.0	0.2	3.3
Bosnia-H	0.2	0.0	0.0	0.3
Bulgaria	0.6	0.0	0.0	0.6
Croatia	0.4	0.0	0.0	0.4
Cyprus	0.2	0.0	0.0	0.2
Czech Republic	1.1	0.2	0.0	1.3
Denmark	1.7	0.1	0.1	2.0
Estonia	0.4	0.0	0.0	0.4
Finland	1.5	0.2	0.1	1.7
France	16.6	6.3	2.1	25.0
Germany	27.6	6.2	3.9	37.7
Greece	3.3	0.3	0.0	3.7
Hungary	0.9	0.1	0.0	1.1
Ireland	1.6	0.2	0.0	1.8
Italy	14.4	1.3	0.6	16.2
Latvia	0.3	0.0	0.0	0.3
Lithuania	0.5	0.0	0.0	0.5
Luxembourg	0.3	0.0	0.0	0.3
Macedonia	0.1	0.0	0.0	0.1
Malta	0.1	0.0	0.0	0.1
Netherlands	8.3	4.2	0.2	12.7
Norway	1.8	3.2	0.8	5.9
Poland	3.9	0.1	0.0	4.0
Portugal	1.8	0.2	0.0	2.0
Romania	1.6	0.0	0.0	1.6
Russia-Kaliningrad	0.1	0.0	0.0	0.1
Russia-Kola/Karelia	0.5	0.3	0.1	0.9
Russia-St Petersburg	0.3	0.0	0.1	0.4
Russia-Remain. Europ.	14.1	8.9	2.2	25.1
Serbia-M	0.4	0.0	0.0	0.4
Slovakia	0.5	0.0	0.0	0.5
Slovenia	0.3	0.1	0.0	0.4
Spain	15.6	1.9	0.4	17.8
Sweden	2.8	0.4	0.1	3.3
Switzerland	3.5	0.0	0.1	3.7
Turkey	5.9	0.3	0.0	6.2
Ukraine	1.9	0.4	0.5	2.9
United Kingdom	19.8	0.3	0.7	20.8
Europe	163.1	35.4	13.2	211.7
Thereof: EU-25	130.1	22.1	9.2	161.5

Table 6.4: Sectoral HFC emissions of the "current legislation" baseline projection in 2020 [Mt CO_2 eq]

Country	COMM	IND	AIRCON	TRA_REF	DOM	MAC	OF	OC	AERO	HCFC22	HFC_OTH
Albania	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Austria	0.8	0.4	0.2	0.2	0.0	0.4	0.3	1.2	0.2	0.0	0.0
Belarus	0.4	0.1	0.0	0.2	0.0	0.1	0.0	0.2	0.3	0.0	0.0
Belgium	1.0	0.5	0.2	0.3	0.0	0.5	0.1	0.2	0.3	0.0	0.1
Bosnia-Herc.	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bulgaria	0.1	0.1	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0
Croatia	0.2	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Cyprus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Czech Rep.	0.3	0.1	0.1	0.1	0.0	0.4	0.0	0.0	0.1	0.0	0.0
Denmark	0.7	0.2	0.1	0.1	0.0	0.2	0.1	0.1	0.2	0.0	0.1
Estonia	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Finland	0.7	0.2	0.1	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.0
France	6.3	2.2	1.3	0.5	0.0	2.3	0.5	0.5	2.4	0.1	0.5
Germany	10.5	4.8	2.4	0.7	0.0	4.9	0.3	2.4	0.6	0.8	0.0
Greece	0.5	0.1	1.4	0.1	0.0	0.5	0.1	0.1	0.1	0.3	0.0
Hungary	0.2	0.1	0.1	0.1	0.0	0.3	0.0	0.0	0.1	0.0	0.0
Ireland	0.4	0.3	0.1	0.2	0.0	0.3	0.0	0.1	0.1	0.0	0.0
Italy	4.6	2.3	1.0	0.3	0.0	2.9	0.5	0.9	1.3	0.1	0.4
Latvia	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Lithuania	0.1	0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Luxembourg	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Macedonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Netherlands	1.6	0.7	0.4	0.5	0.0	0.8	0.2	0.3	0.9	2.9	0.1
Norway	0.5	0.3	0.1	0.0	0.0	0.2	0.1	0.2	0.2	0.0	0.2
Poland	1.3	0.5	0.2	0.0	0.0	1.4	0.1	0.2	0.2	0.0	0.0
Portugal	0.4	0.2	0.3	0.1	0.0	0.4	0.0	0.1	0.1	0.0	0.0
Romania	0.2	0.4	0.0	0.2	0.0	0.6	0.0	0.0	0.0	0.0	0.0
Russia-KALI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6.4 (continued): Sectoral HFC emissions of the "current legislation" baseline projection in 2020 [Mt CO_2 eq]

Country	COMM	IND	AIRCON	TRA_REF	DOM	MAC	OF	OC	AERO	HCFC22	HFC_OTH
Russia-KOLK	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Russia-SPET	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Russia-REMR	3.8	1.4	0.5	0.5	0.3	0.9	0.0	0.0	0.8	5.8	0.0
Serbia-M.	0.1	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Slovakia	0.1	0.1	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0
Slovenia	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Spain	4.3	1.1	3.6	0.7	0.0	2.4	0.2	0.5	0.7	2.0	0.2
Sweden	1.0	0.4	0.2	0.3	0.0	0.3	0.1	0.2	0.3	0.0	0.1
Switzerland	1.1	0.7	0.3	0.2	0.0	0.5	0.1	0.2	0.3	0.0	0.0
Turkey	0.9	0.7	1.4	0.5	0.1	2.0	0.0	0.1	0.2	0.0	0.0
Ukraine	0.8	0.3	0.1	0.2	0.0	0.4	0.0	0.0	0.2	0.0	0.0
UK	6.6	3.1	0.8	0.4	0.0	3.3	1.1	1.6	2.6	0.2	0.1

Table 6.5: Sectoral PFC and SF_6 emissions of the "current legislation" baseline projection in 2020 [Mt CO_2eq]

Country	ALUM_PR	SEMICOND	MAGN	GIS	WIND	SF6_OTH
Albania	0.0	0.0	0.0	0.0	0.0	0.0
Austria	0.0	0.0	0.1	0.0	0.3	0.2
Belarus	0.0	0.0	0.0	0.0	0.0	0.0
Belgium	0.0	0.0	0.0	0.1	0.1	0.0
Bosnia-H.	0.0	0.0	0.0	0.0	0.0	0.0
Bulgaria	0.0	0.0	0.0	0.0	0.0	0.0
Croatia	0.0	0.0	0.0	0.0	0.0	0.0
Cyprus	0.0	0.0	0.0	0.0	0.0	0.0
Czech Rep.	0.0	0.2	0.0	0.0	0.0	0.0
Denmark	0.0	0.1	0.0	0.0	0.1	0.0
Estonia	0.0	0.0	0.0	0.0	0.0	0.0
Finland	0.0	0.2	0.0	0.1	0.0	0.0
France	2.3	3.9	1.1	0.8	0.0	0.2
Germany	1.5	4.7	0.1	0.7	3.0	0.1
Greece	0.1	0.2	0.0	0.0	0.0	0.0
Hungary	0.1	0.0	0.0	0.0	0.0	0.0
Ireland	0.0	0.2	0.0	0.0	0.0	0.0
Italy	0.1	1.2	0.2	0.3	0.0	0.1
Latvia	0.0	0.0	0.0	0.0	0.0	0.0
Lithuania	0.0	0.0	0.0	0.0	0.0	0.0
Luxembourg	0.0	0.0	0.0	0.0	0.0	0.0
Macedonia	0.0	0.0	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0	0.0	0.0
Netherlands	3.8	0.4	0.0	0.2	0.0	0.0
Norway	3.2	0.0	0.8	0.0	0.0	0.0
Poland	0.1	0.0	0.0	0.0	0.0	0.0
Portugal	0.0	0.2	0.0	0.0	0.0	0.0

Table 6.5 (continued): Sectoral PFC and SF_6 emissions of the "current legislation" baseline projection in 2020 [Mt CO_2eq]

Country	ALUM_PR	SEMICOND	MAGN	GIS	WIND	SF6_OTH
Romania	0.0	0.0	0.0	0.0	0.0	0.0
Russia-KALI	0.0	0.0	0.0	0.0	0.0	0.0
Russia-KOLK	0.2	0.1	0.1	0.0	0.0	0.0
Russia-SPET	0.0	0.0	0.0	0.0	0.0	0.0
Russia-REMR	7.8	1.1	0.8	1.4	0.0	0.0
Serbia-M.	0.0	0.0	0.0	0.0	0.0	0.0
Slovakia	0.0	0.0	0.0	0.0	0.0	0.0
Slovenia	0.1	0.0	0.0	0.0	0.0	0.0
Spain	1.4	0.5	0.1	0.2	0.0	0.0
Sweden	0.4	0.0	0.0	0.1	0.0	0.0
Switzerland	0.0	0.0	0.0	0.1	0.0	0.0
Turkey	0.3	0.0	0.0	0.0	0.0	0.0
Ukraine	0.4	0.0	0.2	0.3	0.0	0.0
UK	0.1	0.2	0.2	0.5	0.0	0.0

6.2.3 The mitigation potential from the maximum application of the measures included in GAINS 1.0

The current legislation baseline projection has been contrasted with a scenario that explores the extent to which F-gas emissions could be lowered through full application of all mitigation measures that are currently included in GAINS 1.0.

Results indicate that mitigation measures are available to reduce F-gas emissions in 2020 by 70 percent below the level projected for the current legislation baseline (Table 6.6). This potential is sufficient to compensate by 2020 the growth in HFC related activities, so that compared to 1995 total European F-gas emissions (in CO_2eq) could be reduced by approximately 25 percent. However, due to the limited penetration rate of mitigation measures assumed in the GAINS calculations, F-gas emissions would temporarily increase in 2010 even in this maximum application case.

Table 6.6: F-gas emissions in 2020 achievable through full application of all mitigation measures considered in the GAINS 1.0 model (Mt CO_2eq)

	Emissions in Maximum Feasible Reduction case in 2020				For comparison	
	HFCs	PFCs	SF_6	SUM	Current legislation baseline in 2020	1995
Albania	0.1	0.0	0.0	0.1	0.2	0.0
Austria	1.1	0.0	0.1	1.3	4.3	1.7
Belarus	0.6	0.0	0.0	0.6	1.4	0.0
Belgium	1.1	0.0	0.1	1.1	3.3	0.4
Bosnia-H	0.1	0.0	0.0	0.1	0.3	0.1
Bulgaria	0.1	0.0	0.0	0.1	0.6	0.0
Croatia	0.2	0.0	0.0	0.2	0.4	0.0
Cyprus	0.0	0.0	0.0	0.0	0.2	0.0
Czech Republic	0.3	0.0	0.0	0.3	1.3	0.0
Denmark	0.7	0.0	0.0	0.7	2.0	0.3
Estonia	0.1	0.0	0.0	0.1	0.4	0.0
Finland	0.5	0.0	0.0	0.5	1.7	0.1
France	6.8	0.4	0.1	7.3	25.0	8.7
Germany	7.5	0.4	1.3	9.2	37.7	20.0
Greece	0.7	0.1	0.0	0.8	3.7	0.7
Hungary	0.3	0.0	0.0	0.3	1.1	0.1
Ireland	0.5	0.0	0.0	0.5	1.8	0.1
Italy	5.2	0.1	0.0	5.4	16.2	3.8
Latvia	0.1	0.0	0.0	0.1	0.3	0.0
Lithuania	0.1	0.0	0.0	0.1	0.5	0.0
Luxembourg	0.1	0.0	0.0	0.1	0.3	0.0
Macedonia	0.0	0.0	0.0	0.0	0.1	0.0
Malta	0.0	0.0	0.0	0.0	0.1	0.0
Netherlands	5.0	0.2	0.0	5.3	12.7	7.1
Norway	0.8	0.5	0.0	1.3	5.9	3.0
Poland	1.1	0.0	0.0	1.2	4.0	0.2
Portugal	0.5	0.0	0.0	0.5	2.0	0.1
Romania	0.3	0.0	0.0	0.3	1.6	0.0
Russia-KALI	0.0	0.0	0.0	0.0	0.1	0.0
Russia-KOLK	0.2	0.0	0.0	0.2	0.9	0.2
Russia-SPET	0.1	0.0	0.0	0.1	0.4	0.1
Russia-REMR	9.5	0.6	0.2	10.4	25.1	20.5
Serbia-M	0.1	0.0	0.0	0.2	0.4	0.0
Slovakia	0.1	0.0	0.0	0.2	0.5	0.1
Slovenia	0.1	0.1	0.0	0.1	0.4	0.0
Spain	5.6	0.2	0.0	5.9	17.8	7.4
Sweden	1.0	0.0	0.0	1.1	3.3	0.5
Switzerland	1.2	0.0	0.0	1.2	3.7	0.0
Turkey	0.8	0.0	0.0	0.9	6.2	0.3
Ukraine	0.7	0.0	0.0	0.8	2.9	1.4
United Kingdom	7.7	0.1	0.1	7.9	20.8	9.4
Europe	61.0	3.0	2.3	66.2	211.7	86.7
Thereof: EU-25	46.2	1.7	1.9	49.8	161.5	60.9

6.3 Costs estimates

6.3.1 Unit costs of mitigation

A number of relatively cheap options exist to control emissions of F-gases. Table 6.7 summarizes the costs computed by GAINS for the mitigation options considered in the model. While this table presents average costs over all countries, unit costs vary across countries due to country-specific factors. The table presents unit costs in terms of CO_2eq as well as marginal costs for options that replace less efficient options at higher costs. These marginal costs relate the extra costs for using an additional measure to the extra emission reduction achieved by that measure.

6.3.2 Cost estimates for individual countries

For each country, costs for implementing the "current legislation" as well as for applying all measures contained in the GAINS 1.0 database can be estimated by combining the unit costs presented above with the country-specific application factors and activity rates.

Mitigation potentials and associated costs for the regions considered in GAINS 1.0 are presented in Table 6.8. The autonomous technological development and measures included in current legislation are computed to reduce F-gas emissions by approximately 50 Mt CO_2eq in 2020 compared to a strict no-control case. GAINS estimates the associated costs at 925 million €/yr. Full implementation of the available mitigation measures could triple the mitigation volume to approximately 150 Mt CO_2eq, while costs increase by more than a factor of four.

Table 6.7: Summary of emission control costs of the F-gas mitigation options considered in GAINS (average costs for the model domain)

GAINS sector acronym	GAINS technology acronym	Control option	Average unit costs [€/t CO_2eq]	Marginal costs [€/t CO_2eq]	Maximum mitigation potential in 2020 [Mt CO_2eq]	Costs of full application in 2020 [million €/year]
MAGNPR	ALT_MAGN	SO_2 cover gas	0.1	0.1	3.7	0.4
WIND_B	ALT_WIND	Alternatives	0.1	0.1	2.2	0.1
SF6_OTH	ALT_SF	Alternatives	0.1	0.1	0.5	0.2
HCFC22	INC_HFC	Incineration	0.3	0.3	1.0	0.3
OC	ALT_OC	Alternative propellants	0.5	0.5	7.9	3.9
AERO	ALT_PROP	Alternative propellants	1.0	1.0	1.0	1.0
ALU_SWPB	RETSWPB	SWPB retrofit	1.4	1.4	0.0	0.0
TRA_REFB	ALT_TRAB	Alternative refrigerant-bank	2.0	2.0	3.6	7.1
TRA_REFS	ALT_TRAS	Alternative refrigerant-scrap	2.0	2.0	0.0	0.0
ALU_SWPB	CONVSWPB	SWPB to PFPB conversion	2.8	3.3	6.8	22.5
GIS	GP_GIS	Good practice	3.6	3.6	4.5	16.1
OF	ALT_OF	Alternative blowing agents	4.9	4.9	1.3	6.2
ALU_VSS	RETVSS	VSS retrofitting	7.1	7.1	0.0	0.0
DOM_S	GP_DOMS	Recollection	14.6	14.6	0.3	4.6
IND_B	GP_INDB	Good practice-bank	15.1	15.1	2.1	31.7
IND_S	GP_INDS	Good practice-scrap	15.1	15.1	0.0	0.3
TRA_REFB	GP_TRAB	Good practice-bank	17.8	17.8	2.9	51.9
TRA_REFS	GP_TRAS	Good practice-scrap	17.8	17.8	0.0	0.5
COMM_B	GP_COMMB	Good practice-bank	18.1	18.1	3.2	57.9
COMM_S	GP_COMMS	Good practice-scrap	18.1	18.1	1.4	25.9
MAC_B	GP_MACB	Good practice-bank	22.7	22.7	0.0	0.0
MAC_S	GP_MACS	Good practice-scrap	22.7	22.7	0.4	8.0
SEMICOND	ALT_SOLV	Alternatives	26.0	26.0	13.1	339.8
MAC_B	ALT_MACB	Alternative refrigerant-bank	25.6	30.6	23.3	712.5
MAC_S	ALT_MACS	Alternative refrigerant-scrap	25.6	30.6	0.0	0.0
COMM_B	PM_COMMB	Process modification-bank	24.6	31.7	27.2	863.1
COMM_S	PM_COMMS	Process modification-scrap	24.6	31.7	0.0	0.0
IND_B	PM_INDB	Process modification-bank	21.3	32.1	12.7	406.8
IND_S	PM_INDS	Process modification-scrap	21.3	32.1	0.0	0.0
AIRCON_B	GP_STATB	Good practice-bank	38.9	43.1	0.1	5.3
AIRCON_S	GP_STATS	Good practice-scrap	38.9	43.1	0.0	0.6
ALU_VSS	CONVVSS	VSS to PFPB conversion	39.3	55.7	12.5	698.4
AIRCON_B	PM_STATB	Process modification-bank	49.8	64.2	13.6	873.2
AIRCON_S	PM_STATS	Process modification-scrap	49.8	64.2	0.0	0.0

Table 6.8: Mitigation volumes and emission control costs in the year 2020 for the "current legislation" (CLE) and maximum mitigation (MFR) cases

	Current legislation projection for 2020		Maximum mitigation case for 2020	
	Mitigation volume [Mt CO_2eq]	Mitigation costs [million €/yr]	Mitigation volume [Mt CO_2eq]	Mitigation costs [million €/yr]
Albania	0.0	0.0	0.1	1.9
Austria	0.8	16.7	3.0	47.9
Belarus	0.0	0.0	0.8	13.3
Belgium	0.9	20.5	2.2	57.5
Bosnia-H.	0.0	0.0	0.1	2.4
Bulgaria	0.0	0.0	0.5	11.5
Croatia	0.0	0.0	0.3	5.4
Cyprus	0.0	1.0	0.1	3.0
Czech Republic	0.4	8.9	1.0	27.5
Denmark	0.5	11.4	1.3	35.0
Estonia	0.1	2.2	0.3	7.4
Finland	0.5	11.0	1.2	34.8
France	6.4	110.9	17.7	418.4
Germany	9.6	194.5	28.5	716.5
Greece	1.4	38.4	2.9	118.3
Hungary	0.3	5.3	0.8	24.2
Ireland	0.5	9.8	1.3	34.8
Italy	7.6	105.4	10.8	318.5
Latvia	0.1	2.2	0.2	6.4
Lithuania	0.2	3.5	0.4	10.3
Luxembourg	0.1	2.2	0.2	5.9
Macedonia	0.0	0.0	0.1	1.8
Malta	0.0	0.5	0.1	1.4
Netherlands	1.5	33.1	7.5	113.8
Norway	0.5	10.3	4.6	182.7
Poland	1.6	33.2	2.8	88.4
Portugal	0.6	15.6	1.4	46.4
Romania	0.0	0.0	1.3	31.3
Russia-KALI	0.0	0.0	0.1	1.9
Russia-KOLK	0.0	0.0	0.7	24.0
Russia-REMR	0.0	0.0	14.7	539.2
Russia-SPET	0.0	0.0	0.3	8.1
Serbia-M.	0.0	0.0	0.3	5.7
Slovakia	0.1	2.6	0.4	10.1
Slovenia	0.1	1.9	0.3	7.2
Spain	5.2	144.9	11.9	466.3
Sweden	0.8	17.8	2.3	70.3
Switzerland	1.1	24.2	2.4	68.5
Turkey	0.0	0.0	5.4	196.0
Ukraine	0.0	0.0	2.1	52.0
UK	9.8	120.5	13.0	343.8
Total	50.9	948.5	145.4	4159.7

6.3.3 Cost functions

The relation between emission control costs and the associated emission control potentials can be displayed in form of cost functions. Based on the calculated unit cost, the cost curve is first constructed for each sector and then for the whole region (country). This approach employs the principle that technologies characterized by higher costs and lower reduction efficiencies are considered inefficient and excluded from further analysis. The marginal costs (costs of abated F-gas emissions by a given control technology) are calculated for each sector. The remaining options are then ranked according to increasing marginal costs to form the cost curve for the country being considered. This curve presents, for different levels of emission reductions, marginal abatement costs in €/t CO_2eq.

Cost functions are specific to each source region reflecting the different relative contributions from the different emission sources.

Figure 6.4 presents a combined cost function for all F-gases for France for the year 2020, showing the measures that remain after implementation of the current legislation. The information underlying the cost curve can also be displayed in tabular form. Table 6.9 shows such data for France, listing technology acronyms, marginal costs (in €/ton pollutant removed), emissions reduced (in Mt CO_2eq/yr) and total reduction costs (in million €/yr) for the CLE and MFR scenarios, respectively.

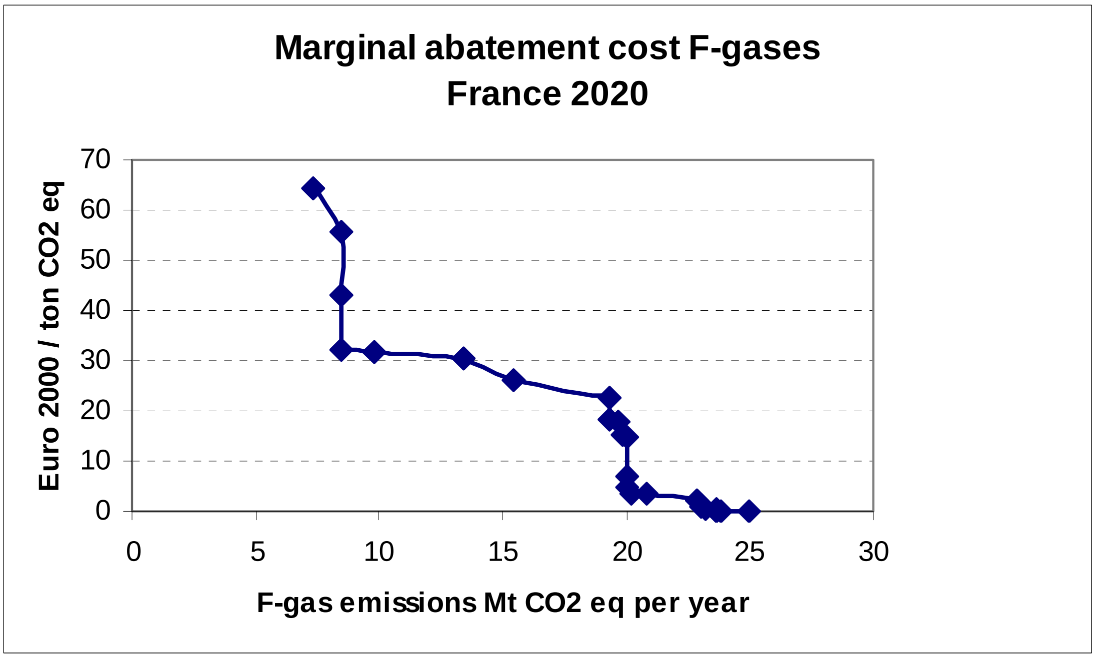

Figure 6.4: Marginal abatement cost curve for France in 2020 for the reduction of F-gas emissions on top of the measures forming part of the current legislation (CLE) case

Table 6.9: The cost curve for France for the year 2020

GAINS technology acronym	Marginal cost	Mitigation volume in CLE case	Remaining emissions in CLE	Total reduction cost CLE	Mitigation potential for MFR*)	Remaining emissions in MFR	Costs of MFR*)
	€/t CO_2eq	Mt CO_2eq	Mt CO_2eq.	Million €/yr	Mt CO_2eq.	Mt CO_2eq.	Million €/yr
		0	31.4		0	25.0	
ALT_MAGN	0.1	0.0	31.4	0.0	1.1	23.8	0.1
ALT_SF	0.1	0.0	31.4	0.0	0.1	23.7	0.0
ALT_WIND	0.1	0.0	31.4	0.0	0.0	23.7	0.0
INC_HFC	0.3	1.4	30.0	0.4	0.0	23.7	0.0
ALT_OC	0.5	0.0	30.0	0.0	0.5	23.2	0.2
ALT_PROP	1.0	0.0	30.0	0.0	0.2	23.0	0.2
RETSWPB	1.4	0.0	30.0	0.0	0.0	23.0	0.0
ALT_TRAB	2.0	0.0	30.0	0.0	0.2	22.9	0.3
ALT_TRAS	2.0	0.0	30.0	0.0	0.0	22.9	0.0
CONVSWPB	3.3	0.0	30.0	0.0	2.0	20.8	6.7
GP_GIS	3.6	0.0	30.0	0.0	0.6	20.2	2.3
ALT_OF	4.9	0.0	30.0	0.0	0.2	20.0	0.9
RETVSS	7.1	0.0	30.0	0.0	0.0	20.0	0.0
GP_DOMS	14.6	0.2	29.9	2.2	0.0	20.0	0.0
GP_INDB	15.1	0.0	29.9	0.0	0.2	19.8	2.6
GP_INDS	15.1	0.8	29.1	11.5	0.0	19.8	0.0
GP_TRAB	17.8	0.0	29.1	0.0	0.1	19.7	2.4
GP_TRAS	17.8	0.0	29.1	0.6	0.0	19.7	0.0
GP_COMMB	18.1	0.0	29.1	0.0	0.4	19.3	6.9
GP_COMMS	18.1	2.3	26.8	41.4	0.0	19.3	0.0
GP_MACB	22.7	0.0	26.8	0.0	0.0	19.3	0.0
GP_MACS	22.7	1.1	25.6	26.7	0.0	19.3	0.0
ALT_SOLV	26.0	0.0	25.6	0.0	3.9	15.4	101.0
ALT_MACB	30.6	0.0	25.6	0.0	2.0	13.4	61.0
ALT_MACS	30.6	0.0	25.6	0.0	0.0	13.4	0.0
PM_COMMB	31.7	0.0	25.6	0.0	3.7	9.8	116.0
PM_COMMS	31.7	0.0	25.6	0.0	0.0	9.8	0.0
PM_INDB	32.1	0.0	25.6	0.0	1.3	8.5	42.4
PM_INDS	32.1	0.0	25.6	0.0	0.0	8.5	0.0
GP_STATB	43.1	0.0	25.6	0.0	0.0	8.5	0.0
GP_STATS	43.1	0.7	25.0	28.0	0.0	8.5	0.0
CONVVSS	55.7	0.0	25.0	0.0	0.0	8.5	0.0
PM_STATB	64.2	0.0	25.0	0.0	1.1	7.3	75.3
PM_STATS	64.2	0.0	25.0	0.0	0.0	7.3	0.0
		6.4		**110.9**	**17.7**		**418.4**

*) on top of CLE

7 Conclusions

A methodology has been developed to estimate emissions of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), as well as the options and costs for emission reduction. Emission factors and activity data were identified for the most relevant sectors emitting F-gases. Due to the lack of reported activity data for many countries, the uncertainty surrounding the estimates is large. The initial results from the GAINS 1.0 model suggest that:

- Total emissions of F-gases in the EU25 might grow by a factor of two to three between 1995 and 2020 in spite of existing legislation, making it more challenging for the EU to meet its Kyoto commitment after 2010.
- In the rest of Europe (including the European part of Russia and Turkey) these emissions might double from 1995 to 2020.
- In 2020, air conditioning and refrigerator sectors will become the most important contributors to F-gas emissions, followed by the aluminium industry.
- A total of 34 options to mitigate F-gases and their costs have been identified and implemented in GAINS 1.0. Marginal costs per ton CO_2eq abated of these options range from 0.1 to 64 €/tCO_2eq. More than half of these options have costs below 20 €/tCO_2eq.

The major uncertainties affecting the above results are:

- Uncertainties in the emission factors and activity pathways, especially for mobile and stationary air conditioning.
- Uncertainties in the future penetration of mobile air conditioning and use of HFC based refrigerants in cooling sectors.
- Differences in the global warming potentials of sectoral emissions between countries, caused by different composition of emission sources emitting different F-gases.
- Lack of data on the actual activity levels of F-gas emitting sources in a large number of countries.

References

AEAT (2003) Emissions and projections of HFCs, PFCs and SF_6 for the UK and Constituent Countries, Draft Final Report prepared for the Department for Environment, Food and rural Affairs, ED50090 Draft F, AEATechnology, Culham (UK).

Devotta S., Asthana S., Joshi R. (2004) Challenges in recovery and recycling of refrigerants from Indian refrigeration and air-conditioning service sector, Atmospheric Environment, 38: 845-854.

EC (1999) Auto-Oil II Study. CEC, Brussels.

EC (2000) Regulation (EC)No 2037/2000 of the European Parliament and of the Council on substances that deplete the ozone layer 29.6.2000

EC (2003)Consultation paper: how to considerably reduce greenhouse gas emissions fue to mobile air conditioners. European Commission, DGEnvironment, February 2003, Brussels.

EC (2003b) European energy and transport: Trends to 2030. European Commission, KO-AC-02-001-EN-C, ISBN 92-894-4444-4, Luxembourg.

EC (2003c) Proposal for a regulation of the European Parliament and of the Council of certain fluorinated greenhouse gases. Commission of the European Communities, COM(2003)492, final.

EU (2002) Directive 2000/53/EC on end-of life vehicles, Official Journal L 269, 21/10/2000, p 0034-0043.

EU (2003) Directive 2002/96/EC on waste on electric and electronic equipment of 17 January 2003, Official Journal L37, 13/02/2003, p. 24-37.

Eurostat (2001), EU Energy and Transport in Figures, Statistical pocketbook, European Commission, 195p, Belgium.

EUROSTAT (2003) Energy and transport in figures. Statistical pocketbook 2003, European Communities, Brussels.

Harnisch, J, I. Sue Wing, H.D. Jacoby, R.G. Prinn (1998); Primary Aluminum Production: Climate Policy, Emissions and Costs; MIT-Joint Program on the Science andPolicy of Global Change Report Series, Report No. 44. 18p. (Revised version).

Harnisch, J., and Hendriks, C., (2000) Economic Evaluation of Emission Reductions of HFCs, PFCs and SF_6 in Europe, Special Report. Ecofys, Utrecht..

Harnisch, J. and Schwarz, W. (2003) Costs and the impact on emissions of potential regulatory framework for reducing emissions of hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride (B4-3040/2002/336380/MAR/E1), Final Report, Ecofys and Oko-Recherche, Utrecht..

Heijnes, H., van Brummelen M., Blok K. (1999), Reduction of the emissions of HFC's, PFC's and SF_6 in the European Union, Final Report, Ecofys, Utrecht.

Houghton, T., L.G. Meira Filho, B. Lim, K. Tréanton, I. Mamaty, Y. Bonduki, D.J. Griggs and B.A. Callander (eds.)(1997a). Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Vol. 2: Workbook. Paris, IPCC/OECD/IEA.

Houghton, T., L.G. Meira Filho, B. Lim, K. Tréanton, I. Mamaty, Y. Bonduki, D.J. Griggs and B.A. Callander (eds.).(1997b). Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Vol. 3: Greenhouse Gas Inventory Reference Manual. Paris, IPCC/OECD/IEA.

Jyrkkonen M. (2004), Suora kaytto kuljetusjaahdytyksessa (Direct use in refrigerated transport), presentation in seminar: Hiilidioksidi jaahdytyslaitoksissa (CO_2 in refrigeration units), 10.2.2004. Helsinki, Finland.

Kaapola, E. (1989) Pienkylmalaitoksen kayttajaopas (Guide for using refrigerator devices). Kylmatuki, Helsinki. (in Finnish).

Klaassen, G., M. Amann, C. Berglund, J. Cofala, L. Höglund-Isaksson, C. Heyes, R. Mechler, A. Tohka, W. Schöpp and W. Winiwarter. IR-04-015, IIASA, Laxenburg.

Klimont Z., Cofala J., Berto I., Amann M., Heyes C., Gyarfas F., Modelling Particulate Emissions in Europe, IR-02-076, IIASA, Laxenburg.

Kokorin A. and Nakhutin A. (2000) Inventory of non-CO_2 GHG and firs estimates of emissions of New Gases in Russia, In: van Ham J., A. Baede, R. Guicherit, L.A. Meyer and R. Ybema(eds.) Non-CO_2 Greenhouse Gases: Scientific Understanding, control options and policy aspects. Kluwer Academic Publishers, Dordrecht, p.217-222.

Mantzos, L., P. Capros, N. Kouvaritakis, M. Zeka-Paschou, J. Chesshire and J.F.Guilmot (2003) European energy and transport: Trends to 2030. European Commission, KO-AC-02-001-EN-C, ISBN 92-894-4444-4, Luxembourg.

Nakićenović, N., J. Alcamo, Davis, G., de Vries, B., Fenhann, J., *et al.*, 2000, Special Report on Emissions Scenarios (SRES), A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Oinonen T. and Soimakallio S. (2001) HFC- ja PFC- yhdisteiden sekä SF_6:n päästöjen tekniset vähentämiskeinot ja niiden kustannukset Suomessa (HFC and PFC compounds and SF_6 emission reduction options and costs in Finland), VTT tiedotteita 2099 (in Finnish).

Olivier, J. (2002). Part III: Greenhouse gas emissions. In: "CO_2 emissions from fuel combustion 1971-2000", 2002 Edition, pp. III.1-III.31. International Energy Agency (IEA), Paris.

Pedersen P. (1998). Substitutes for Potent Greenhouse Gases (HFCs, PFCs and SF_6), Danish Technological Institute, Denmark.

Peek, K. (2004) Personal communication. June 24th, RIVM, Bilthoven.

Poulsen T. (2001) Ozone depleting substances and the greenhouse gases HFCs, PFCs and SF_6, Danish consumption and emissions 2001, Danish Environmental Protection Agency, Copenhagen Denmark.

RIVM/TNO (2004) EDGAR 3.3. RIVM/TNO, Bilthoven.

Schaefer, D.O. Bartos, S., Blackman, J. 2002, Estimating SF_6 Emissions from Electrical Equipment and Magnesium Production and Processing in the U.S., In: van Ham J., A. Baede, R. Guicherit and J Williams-Jacobse (eds.) Non-CO_2 Greenhouse Gases: Scientific Understanding, control options and policy aspects.Millpress, Rotterdam. p.207-212,.

Schwarz W. (2001) Emission of Refrigerant R-134a from Mobile Air-Conditioning Systems, Annual Rate of Emission from Passenger-Car Air-Conditioning Systems up to Seven Years Old. Study conducted for the German Federal Environment Office, 51p.

Schwarz W. and A. Leisewitz (1999) Emissions and Reduction Potentials of Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride in Germany. Report for the German Federal Environmental Agency (Umweltbundesamt, UBA, Berlin).

Schwarz W. and Harnisch J, (2003) Establishing the Leakage Rates of Mobile Air Conditioners, Final report prepared for the European Commission.

Taylor L. E. Hillier J. A., Mills A. J. White R., Naden J., Bartlett E. L. (2003) World Mineral Statistics 1997-2001 Europe, Production, Exports, Imports, British Geological Survey, Keyworth (UK).

USDOS (1999) U.S. Voluntary PFC Emission Reduction Partnership for . Ways and means of limitng HFC, PFCs and SF6 pursuant decision 13/CP.4. 16 July 1999. Department of State, Office of Global Change.

USEPA (2001a) US High GWP gas emissions 1990-2010: Inventories, projections and opportunities for reductions June 2001. USEPA EPA 000-F-97-000, Washington.

USEPA (2001b) Non- CO_2 Greenhouse Gas Emissions from Developed Countries: 1990-2010, USEPA EPA 430-R-01-007, Washington.

UNEP (1997) Update of the Handbook from the international treaties for the protection of the ozone layer, The Ozone Secretariat, United Nations Environment Programme, Nairobi.

Victor D., MacDonald G. (1999), A Model for Estimating Future Emissions of Sulphur Hexafluoride and Perfluorocarbons, Climatic Change 42: 633-662.

Annex 1

Global warming potentials for different time horizons as defined by UNFCCC (Source: http://ghg.unfccc.int/gwp.html, visited last 18.04.2005)

Species	Chemical formula	Lifetime (years)	Global Warming Potential (Time Horizon)		
			20 years	100 years	500 years
CO_2	CO_2	variable §	1	1	1
Methane *	CH_4	12±3	56	21	6.5
Nitrous oxide	N_2O	120	280	310	170
HFC-23	CHF_3	264	9100	11700	9800
HFC-32	CH_2F_2	5.6	2100	650	200
HFC-41	CH_3F	3.7	490	150	45
HFC-43-10mee	$C_5H_2F_{10}$	17.1	3000	1300	400
HFC-125	C_2HF_5	32.6	4600	2800	920
HFC-134	$C_2H_2F_4$	10.6	2900	1000	310
HFC-134a	CH_2FCF_3	14.6	3400	1300	420
HFC-152a	$C_2H_4F_2$	1.5	460	140	42
HFC-143	$C_2H_3F_3$	3.8	1000	300	94
HFC-143a	$C_2H_3F_3$	48.3	5000	3800	1400
HFC-227ea	C_3HF_7	36.5	4300	2900	950
HFC-236fa	$C_3H_2F_6$	209	5100	6300	4700
HFC-245ca	$C_3H_3F_5$	6.6	1800	560	170
Sulphur hexafluoride	SF_6	3200	16300	23900	34900
Perfluoromethance	CF_4	50000	4400	6500	10000
Perfluoroethane	C_2F_6	10000	6200	9200	14000
Perfluoropropane	C_3F_8	2600	4800	7000	10100
Perfluorobutane	C_4F_{10}	2600	4800	7000	10100
Perfluorocyclobutane	$c\text{-}C_4F_8$	3200	6000	8700	12700
Perfluoropentane	C_5F_{12}	4100	5100	7500	11000
Perfluorohexane	C_6F_{14}	3200	5000	7400	10700

§ Derived from the Bern carbon cycle model.