Supplementary material to:

Global emissions of fluorinated greenhouse gases 2005-2050 with abatement potentials and costs

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Contents

S1. Introduction

This is a description by sector of the estimations of global anthropogenic emissions of F-gases (HFC, PFC and SF_6) presented in the paper "Global emissions of fluorinated greenhouse gases 2005-2050 with abatement potentials and costs." It provides further insights into the details of the activity data, estimations of emissions, mitigation potentials and associated costs as well as a discussion of the most important sources for uncertainty in the sector estimates.

S2. F-gas emission estimations by sector

S2.1 Hydrofluorocarbon (HFC) emissions

In compliance with the Montreal protocol (MP), many sectors that formerly used the highly ozone-depleting substances (ODS) chlorofluorocarbons (CFCs) refrigerants changed rapidly to applications employing hydrochlorofluorocarbons (HCFCs) with lower ozone-depleting effects or hydrofluorocarbons (HFCs) with no ozone-depleting effects (IPCC/TEAP, 2005). Later, amendments to the MP require a complete phase-out of all ODS including HCFCs (UNEP, 2007). In the GAINS model, 14 different sources of HFC or HCFC emissions have been identified, whereof 8 are related to refrigeration and air conditioning. Table S1 presents sub-sectors distinguished in GAINS for HFC or HCFC emissions. Emissions from refrigeration and air conditioning sources are split by emissions from leakage from equipment in use and emissions from scrapping of the equipment at the end-of-life. In addition, for each emission source the fraction of HCFC to HFC in use is identified and modeled following the phase-out schedule of HCFCs in the latest revision of the MP.

Table S1. Sub-sectors distinguished in GAINS for HFC emissions

GAINS sectors	Description
AERO	Aerosols
CAC_B	Stationary air conditioning (commercial sector) using water chilling, emissions banked in equipment
CAC_S	Stationary air conditioning (commercial sector) using water chilling, emissions from scrapped equipment
COMM_B	Commercial refrigeration, emissions banked in equipment
COMM_S	Commercial refrigeration, emissions from scrapped equipment
DOM_S	Domestic small hermetic refrigerators, emissions from scrapped equipment
FEXT_B	Fire extinguishers, emissions banked in equipment
FEXT_S	Fire extinguishers, emissions from scrapped equipment
GSHP_B	Ground source heat pumps, emissions banked in equipment
GSHP_S	Ground source heat pumps, emissions from scrapped equipment
HCFC22_E	HCFC-22 production for emissive use
HCFC22_F	HCFC-22 production for feedstock use
HFC_OTH	Other (e.g. cleansing, micro etching, semiconductor industry, etc.)
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_RD_HDB_B	Mobile air conditioning in buses, emissions banked in equipment
TRA_RD_HDB_S	Mobile air conditioning in buses, emissions from scrapped equipment
TRA_RD_LD4C_B	Mobile air conditioning in cars, emissions banked in equipment
TRA_RD_LD4C_S	Mobile air conditioning in cars, emissions from scrapped equipment
TRA_RD_LD4T_B	Mobile air conditioning in light duty trucks, emissions banked in equipment
TRA_RD_LD4T_S	Mobile air conditioning in light duty trucks, emissions from scrapped equipment
TRA_RD_HDT_B	Mobile air conditioning in heavy duty trucks, emissions banked in equipment
TRA_RD_HDT_S	Mobile air conditioning in heavy duty trucks, emissions from scrapped equipment
OC	Polyurethane one component foam
OF	Other foam
RAC_B	Stationary air conditioning (residential sector) using water chilling, emissions banked in equipment
RAC_S	Stationary air conditioning (residential sector) using water chilling, emissions from scrapped equipment
SOLV_PEM	Solvents
TRA_REFB	Refrigerated transport, emissions banked in equipment
TRA_REFS	Refrigerated transport, emissions from scrapped equipment

HFC emissions from different sectors are calculated using an emission factors approach where general assumptions are used for leakage rates at different stages of HFC use and at disposal at the end of life of appliance and equipment. To the extent available, source-specific leakage rates are taken from published literature (IPCC/TEAP, 2005; IPCC, 2007a; Gschrey et al., 2011; Schwarz et al., 2011; Chaturvedi et al., 2015). Emission factors are sector specific with GWPs determined on the basis of the sector-specific shares of different types of HFCs commonly used and their respective GWPs. Table S2 presents GWPs used in GAINS, expressed in CO_2 equivalents over 100 years, as presented in the IPCC Fourth Assessment Report (AR4) (IPCC, 2007b) and now adopted for policy purposes in the Kyoto protocol. GWP's associated with perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6) are also presented in Table S2.

Table S2. Sector specific global warming potentials (GWPs) used in GAINS

Sector	Type and share of different types of refrigerants	Global warming potential		
		IPCC (AR2)	IPCC (AR4)	IPCC (AR5)
Aerosol	HCFC-141b	713	725	782
	HFC-134a	1300	1430	1550
Stationary air-conditioning*	HCFC-22	1780	1810	1760
	87% HFC-410A and 13% HFC-134a	1670	2002	2018
Commercial refrigeration	HCFC-22	1780	1810	1760
	HFC-134a (25%)/ HFC-404A (70%)/ HFC-410A (5%)	2693	3207	3237
Domestic refrigeration	HFC-134a	1300	1430	1550
Fire extinguishers	Halon-1211/Halon-1301	4445	4515	4020
	HFC-236fa (50%)/HFC-227ea (47.5%)/HFC-23 (2.5%)	4820	6805	6805
Ground source heat pumps	HCFC-22	1780	1810	1760
	HFC-410A	1725	2088	1924
Industrial refrigeration	HCFC-22	1780	1810	1760

	HFC-134a (62%)/ HFC-404A (37%)/ HFC-23 (1%)	2129	2486	2560
Mobile air conditioning**	HFC-134a	1300	1430	1550
Refrigerated transport	HCFC-22	1780	1810	1760
	HFC-134a (80%)/ HFC-404A/ HFC-507 (18%)/ HFC-410A (2%)	1661	1892	2363
Foam[+]	HCFC-141b	713	725	782
	HFC-134a (33%)/ HFC-245fa (61%)/ HFC-365mfc (5%)/ HFC-152a (1%)	1098	1141	1181
Other HFC	HCFC-22	1780	1810	1760
	HFC-134a	1300	1430	1550
HCFC-22 production[++]	HFC-23	11700	14,800	12400
Primary Al production	CF_4	6500	7390	6630
Semiconductor industry				
High and mid voltage switches	SF_6	23900	22800	23500
Magnesium production and casting				
Soundproof windows				
Other SF_6				

[*] Stationary air-conditioning includes both commercial and residential air-conditioning
[**] Mobile air-conditioning includes buses, cars, light and heavy duty trucks
[+] Foam includes both one component and other foams
[++] HCFC-22 production for both emissive and feedstock use
Source: (IPCC, 1996; IPCC, 1997; IPCC, 2007b; Gschrey et al., 2011; UNFCCC, 2012; IPCC, 2014)

S2.1.1 Stationary air-conditioning (residential sector)

To estimate emissions from stationary air conditioners (AC's) in the residential sector, we apply a method similar to what has been used in a model described by (McNeil and Letschert, 2007). HFC use for air conditioning depends both on the average HFC consumption per household using air conditioning (kg HFC/unit) and on the fraction of households who own air conditioners (penetration).

$$HFC\ consumption\ =\ Households\ \times Penetration\ \times\ Average\ charge\ size \tag{1}$$

The number of households was calculated by dividing total population by average household size. Data and scenario values for average household sizes are taken from the UN Global Report on Human Settlements 2005 (UN-Habitat, 2005).

We assume that both energy consumption per appliance and the proportion of households owning air conditioners (penetration) depend on climate and income, being higher in warmer and richer places. Penetration in a certain region is formulated as a function of the climate maximum saturation for that region and of the percentage of the climate maximum saturation achieved at that time in the region (availability).

$$Penetration\ =\ Availability\ \times\ Climate\ Maximum\ Saturation \tag{2}$$

The climate maximum saturation is derived from the assumption that current penetration rates in the USA are the maximum for a climate with a given amount of cooling degree days (CDD's). The relationship between maximum saturation and CDD is exponential, as developed by (Sailor and Pavlova, 2003) and corrected to give a maximum of 100 percent by (McNeil and Letschert, 2007) whose equation we have used here. Availability of air conditioners as a function of income is assumed to develop along a logistic function, with a threshold point beyond which ownership increases rapidly. Using data on present day air conditioner penetration in various countries from McNeil and Letschert (2007) we find availability as a function of income

$$Availability = \frac{1}{1+e^{4.152}\times e^{-0.237\times Income/1000}} \quad (3)$$

where income is defined as GDP per capita in purchasing power parity (PPP) and converted to constant Euro 2010.

GDP and population data is taken from the GAINS model in consistency with relevant external scenarios, i.e. the PRIMES model for EU-28 countries Capros et al. (2012) and the IEA's Energy Technology Perspective (ETP) for non-EU countries (IEA/OECD, 2012). Data on cooling degree days and household size is taken from (Baumert and Selman, 2003) and (UN-Habitat, 2005), respectively. Once the number of stationary air conditioners is estimated, the HFC consumption is estimated assuming the average size of each appliance is 2.62 kW (Adnot et al., 2003) (Sailor and Pavlova, 2003) and the average refrigerant charge is 0.25 kg per kW (UNEP, 2011). An annual leakage rate of 11 percent and 13 percent is assumed for unitary air-conditioning systems in developed and developing countries respectively (Gschrey et al., 2011). At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery with recycling or destruction. Servicing emissions are especially high for the informal servicing sector which constitutes a large part of servicing market in developing countries. For India, due to inadvertent releases during servicing of the air-conditioning equipment a higher annual leakage rate of 25 percent is used in this study (Chaturvedi et al., 2015).

The control options available for this source are different good practice options including leakage control, improved components and end-of-life recollection. These options are assumed to remove 30 percent of emissions banked in equipment in use and almost 88 percent of scrapping emissions (Tohka, 2005). Good practice options are being implemented in the EU as part of the different regulations controlling F-gases (Höglund-Isaksson et al., 2013). In countries with no prior national F-gas regulation in EU, full adoption of good practice options is assumed from 2015 onwards. For substantial further emission reductions, the use of HFC-410A (GWP_{100}=2002) and other high GWP blends need to be replaced by an alternative low GWP refrigerant such as HFC-32 (GWP_{100}=675) or HC-290 ($GWP_{100} = 3$) pressurized CO_2 (GWP_{100}=1).

One of the important features of low-GWP HFC alternatives refrigerants (i. e. HFC-32) is their heat transfer capacity. HFC-32 possesses about 1.5 times higher heat transfer capacity than HFC-410A, which means that its charge volume can be up to 30 percent smaller than existing refrigerants, depending on the model design. According to Daikin Europe N.V. (manufacturer of HFC-32 based AC's), HFC-32 is currently being used in more than 6 million air-conditioning units in more than 40 countries worldwide, including Japan, India, Australia, Thailand and several other Asian, Middle East and European countries (Daikin, 2016). In 2012, Godrej & Boyce Mfg. Co. Ltd. launched their first HC-290 split AC's, which was the first in India. Since then, more than 100,000 AC's have been placed on the market (Rajadhyaksha et al., 2015).

In recent years, companies like Honeywell and Dupont have developed and marketed alternative substances with better performances and very short lifetimes of less than a few months. These are known as HFOs (or unsaturated HFCs). E.g. HFO-1234ze with a GWP_{100} of 6 can be used in foam products and HFO-1234yf with a GWP_{100} of 4 can be used in mobile air-conditioners. The suitability of these substances for stationary air conditioners has not yet been confirmed and they are therefore currently not applied in GAINS for this source. Another option would be to use other non-HFC substances with low or zero GWP like hydrocarbons, CO_2, dimethyl ether and other diverse substances used in various types of foam products, refrigeration, air-conditioning and fire protection systems. Switching to these alternatives is typically costly because it involves process modifications (Halkos, 2010), e.g., changing the process type from ordinary to secondary loop systems.

S2.1.2 Stationary air-conditioning (commercial sector)

The GAINS model store data on commercial floor space area for Annex-1 countries (Cofala et al., 2009). The primary data source for this data is the PRIMES model (Capros et al., 2012). For year 2005, the data on commercial floor space area was correlated with GDP/capita as illustrated in Figure S1. Fitting a linear trend line, the following relationship was retrieved:

$$\left[\left(\frac{Commercial\ floor\ space}{Capita}\right) = 0.0003\left(\frac{GDP}{Capita}\right) + 7.1984\right] \qquad (R^2 = 0.6737) \qquad (4)$$

Using GDP per capita as driver, projections for future growth in commercial floor space area were obtained for each country. To estimate the HFC consumption in commercial air conditioning, a sector specific HFC consumption value of 0.02 kg/m^2 was applied (Höglund-Isaksson et al., 2013).

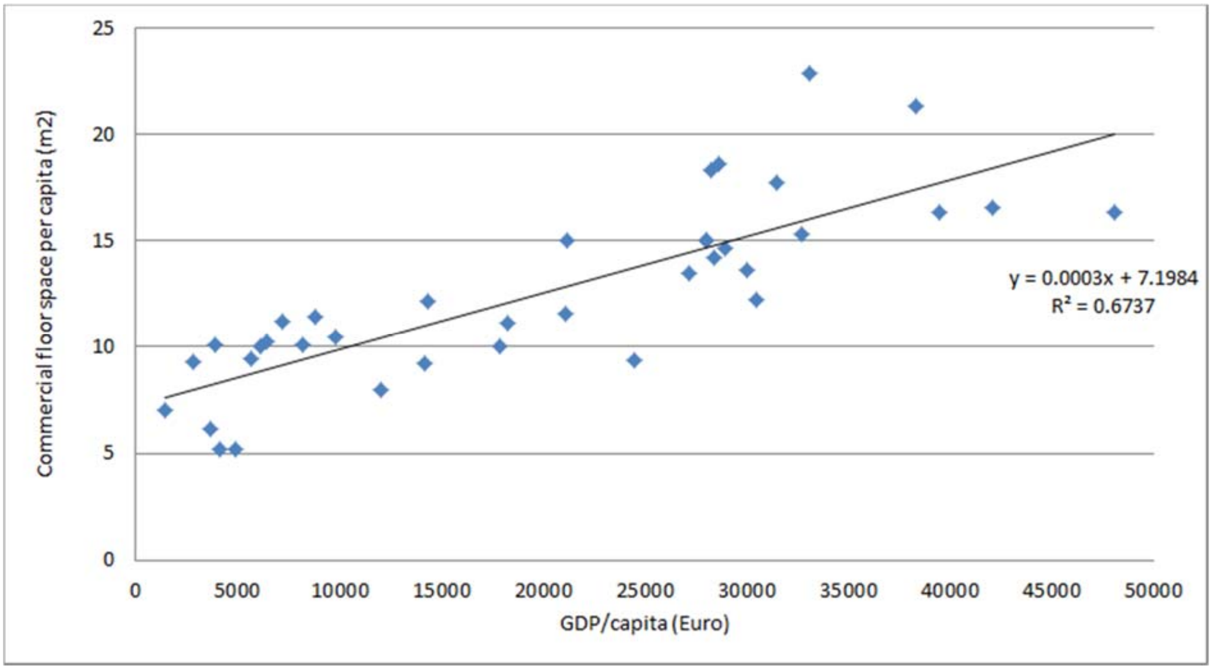

Figure S1. Variation of commercial floor space per capita w.r.t. GDP per capita in year 2005.

Source: PRIMES model.

An annual leakage rate of 11 percent and 13 percent is assumed for unitary air-conditioning systems in developed and developing countries respectively (Gschrey et al., 2013). At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery, recycling or destruction. Control options available for this source are similar to the options discussed for residential air conditioning (Section 2.1.1).

S2.1.3 Domestic refrigeration

For refrigeration in the domestic sector, growth in activity levels follows growth in number of households. Stock of refrigerators and national end use consumption are driven by population growth and trends in appliance ownership rates. In developed countries the market for refrigerators is saturated, i.e., nearly every household owns a refrigerator. Ownership rates are further increased only by ownership of multiple units of each appliance. In developing countries, however, ownership rates of even basic appliances are dynamic, and depend critically on household income level, degree of urbanization and electrification. In countries experiencing rapid growth in those parameters (e.g. China, India, Brazil etc.), appliance ownership growth is dramatic.

The GAINS model utilizes population forecasts in combination with an income model and econometric parameterization to arrive at the national ownership rate for each year in the forecast. The rate of ownership of refrigerator(s) per household is derived using a function estimated by the PAMS[1] model (2012). The general form of the function for the rate of refrigerator ownership per household is given by:

$$Sat_{DOM} = (K \times I_t)^{\lambda_a} \times \left[1 - e^{-\left(bE_t^{\lambda_b} + cU_t^{\lambda_c}\right)}\right]^a \qquad (5)$$

where Sat_{DOM} represents the saturation (rate) of domestic refrigerator ownership, I is the monthly household income given by GDP per household in the country, U is the national urbanization rate, E is the national electrification rate, and t is the year of the projected saturation.

The econometric parameter estimates from the PAMS model were applied to derive the rate of refrigerator ownership per household in GAINS. The number of refrigerators in a country was calculated by multiplying the ownership rate by the number of households in a country (UN-Habitat, 2005). Growth in number of refrigerators is driven by population growth and trends in appliance ownership as estimated above. Once the number of refrigerators is estimated, an average refrigerant charge of 0.1 kg HFC per unit (USEPA, 2010a) is used to estimate the HFC consumption in domestic refrigerators.

As domestic refrigerators are hermetic there is no risk of leakage during use, but there is a risk of emission release during the scrapping phase. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery with recycling or destruction. The control option available for this source is good practice during end-of-life scrapping, which is assumed to remove 80 percent of emissions (Tohka, 2005). The option is already in place in the EU through the F-gas Regulation 2006 (Schwarz et al., 2011). HC-600a (GWP_{100}=3) is widely available for domestic refrigeration applications and suitable components (such as compressors) are widely available (UNEP, 2015a). HFOs are not yet used for this application. Compressors optimized for HFO-1234yf or HFO-1234ze in domestic refrigeration appliances are not yet widely available.

S2.1.4 Commercial refrigeration

Commercial refrigeration includes refrigerated equipment found in supermarkets, convenience stores, restaurants, and other food service establishments (Girotto et al. 2004). Equipment in this end-use typically lasts

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[1] The methodology of the PAMS (Policy Analysis Modeling System) model developed by CLASP (Collaborative Labeling and Appliance Standards Program) is used to estimate the number of domestic refrigerators (see: www.clasponline.org) in this study.

approximately 15–20 years. At present, the commercial refrigeration sector accounts for approximately 32 percent of global HFC consumption or 40 percent of HFC consumption in the refrigeration/AC sector (USEPA 2010b).

Starting point for the estimation of emissions from commercial refrigeration in Annex-I countries in GAINS is the HFC consumption reported by member countries to the United Nations Framework Convention on Climate Change (UNFCCC) for this sector for the years 2005 and 2010. Figure S2 presents the HFC consumption in commercial refrigeration per unit value added for commercial sector in 2005 as reported by Annex-I countries to UNFCCC. As shown, reported rates vary greatly across countries. As we are not able to fully explain the variations in the reported consumption, e.g., by having access to information on consumption patterns for refrigerated goods, we adopt HFC consumption as reported. Projections for future HFC consumption are driven by growth in service sector value added.

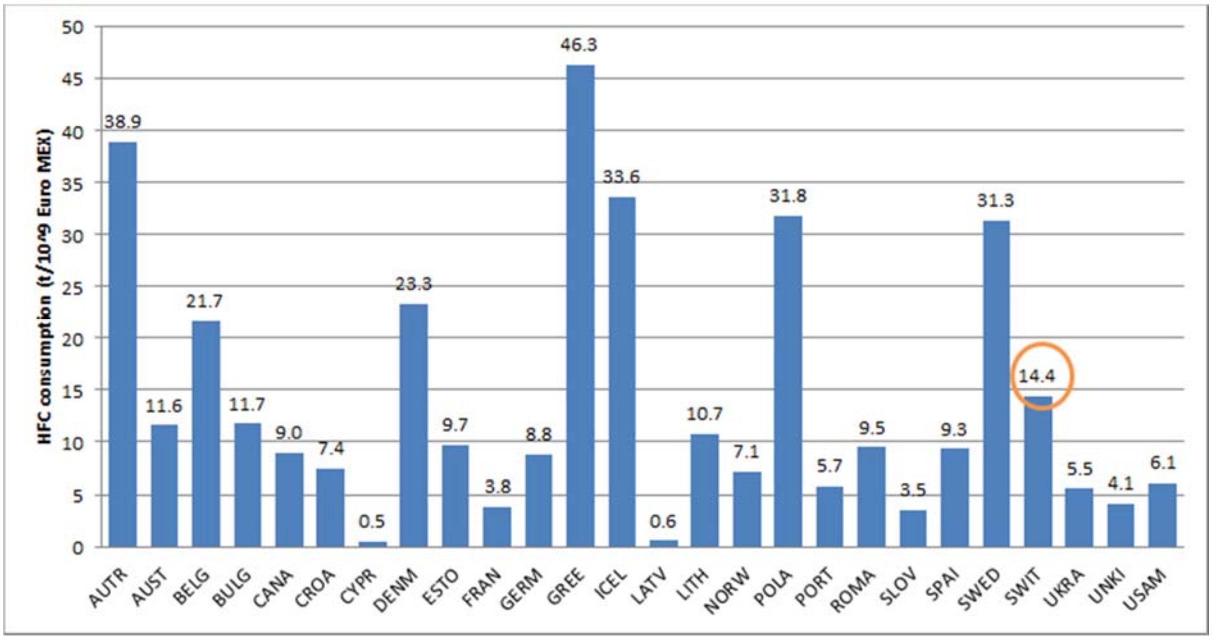

Figure S2. HFC consumption in commercial refrigeration per unit value added for commercial sector in 2005 for Annex-I countries

Source: UNFCCC (2012)

For countries not reporting HFC consumption in this sector, the Swiss consumption rate of 14.4 tonne HFC per billion Euro value added in 2005 has been adopted as default. For 2009-10, HCFC consumption in the commercial refrigeration sector of China was 19.8 tonne HCFC per billion Euro value added (UNEP, 2011) whereas HCFC consumption in the commercial refrigeration sector of India was 1100 tonne in 2005 (MoEF, 2009) or 3.8 tonne HCFC per billion Euro value added. Due to the unavailability of HCFC consumption data for other developing countries, we adopt the Chinese and Indian value as default for HCFC consumption in the commercial refrigeration sector of developing countries in general. Projections for service sector value added are adopted from the macroeconomic scenario by PRIMES baseline scenario (Capros et al., 2013) for EU-28 and IEA/OECD (2012) for non-EU-28 countries. An annual leakage rate of 18 percent for industrialized and 22 percent for developing countries (Gschrey et al., 2011) from equipment in use is applied consistently across all GAINS regions. This leakage mainly reflects losses during refill. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery, recycling or destruction.

The control options available for this source are different good practice options including leakage control, improved components and end-of-life recollection. These options are assumed to remove 33 percent of emissions banked in equipment in use and almost 80 percent of scrapping emissions. For substantial further emission reductions, the use of HFC-134a (GWP_{100}=1430), HFC-404A (GWP_{100}=3922), HFC-410A (GWP_{100}=2088) and other high GWP blends need to be replaced by alternative low GWP refrigerants such as HFC-152a (GWP_{100}=124), hydrocarbons and natural refrigerants (i.e. pressurized CO_2, ammonia etc.). For stand-alone systems, HFO-1234yf and HFO-1234ze are possible alternatives when HCs are restricted by regional safety codes, as they have lower flammability. For condensing units, CO_2 is an option, although getting high efficiency and low capital cost is proving a challenge for condensing units. For new centralized systems, CO_2 is now in widespread use, especially in Europe (UNEP, 2015b).

S2.1.5 Industrial refrigeration

Food processing and cold storage is an important application of industrial refrigeration used for preservation and distribution of food while keeping nutrients intact. On a global scale this application is very significant in size and economic importance (Mohanraj et al. 2009). The application includes cold storage (at temperatures from −1°C to 10°C), freezing (−30°C to −35°C) and the long-term storage of frozen products (−20°C to −30°C). The preferred HFCs used are HFC-134a and HFC blends with a small temperature glide such as HFC-404A, HFC-507A and HFC-410A. Ammonia/CO_2 cascade systems are also being used, as are hydrocarbons as primary refrigerants in indirect systems (IPCC/TEAP 2005).

Starting point for the estimation of emissions from industrial refrigeration in Annex-I countries in GAINS is the HFC consumption reported for this source by member states to the UNFCCC for the years 2005 and 2010. Figure S3 presents the HFC consumption in industrial refrigeration per unit value added for industrial sector in 2005 as reported by Annex-I countries to UNFCCC. As shown, reported rates vary greatly across countries. As we are not able to explain the variations in the reported consumption, we adopt it as activity data as reported. Projections for future HFC consumption are driven by growth in value added for manufacturing industry. For countries not reporting HFC consumption in this sector, the German consumption per value added has been adopted as default. For 2009-10, HCFC consumption in the industrial refrigeration sector of China was 19.8 tonne HCFC per billion Euro value added (UNEP, 2011) whereas HCFC consumption in the industrial refrigeration sector of India in 2005 was 5.9 tonne HCFC per billion Euro value added (MoEF, 2009). Due to the unavailability of HCFC consumption data for other developing countries, we adopt the Chinese and Indian value as default for HCFC consumption in the industrial refrigeration sector of developing countries in general. Projections for manufacturing industry value added are adopted from the macroeconomic scenario by PRIMES baseline scenario (Capros et al., 2013) for EU-28 and IEA/OECD (2012) for non-EU-28 countries.

An annual leakage rate of 11 percent for industrialized and 13.7 percent for developing countries (Gschrey et al., 2011) from industrial refrigeration equipment in use is applied consistently across all GAINS regions. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery with recycling or destruction.

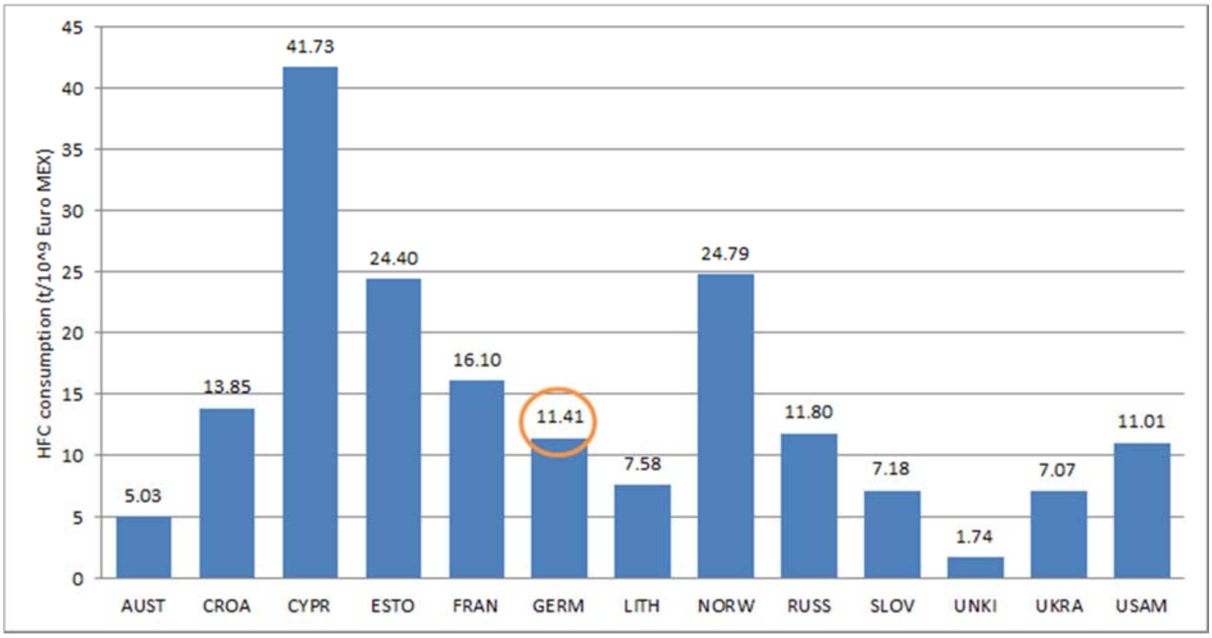

Figure S3. HFC consumption in industrial refrigeration per unit value added for industrial sector in 2005 for Annex-I countries

Source: UNFCCC (2012)

The control options available for this source are different good practice options including leakage control, improved components and end-of-life recollection. These options are assumed to remove 42 percent of emissions banked in equipment in use and almost 90 percent of scrapping emissions (Tohka, 2005). Good practice options are already implemented in the EU and other annex-I countries as part of the different regulations controlling F-gases. For substantial further emission reductions, the use of HFC-134a (GWP_{100}=1430), HFC-404A (GWP_{100}=2088) and other high GWP blends need to be replaced by alternative low GWP refrigerants such as ammonia (NH_3) or pressurized CO_2 (Pearson, 2008; Messineo, 2012).

S2.1.6 Refrigerated transport

Refrigerated road transport includes transportation of food products (fresh, frozen or chilled), pharmaceutical products, and plants/flowers. The type of vehicles used for such transportations are trailers, heavy and small trucks, and vans. Refrigerated road transport vehicles have different capacities; vans are typically below 3.5 tonnes, small trucks and trailers vary between 3.5 to 7.5 tonnes, and heavy trucks have a capacity of more than 7.5 tonnes.

In 2010, there were around 4 million refrigerated vehicles in service worldwide (UNEP, 2010), including vans (40%), trucks (30%), semi-trailers or trailers (30%). These units predominantly use HFC-404A and HFC-410A as refrigerants. HFC-134a is also used for chilled distribution only vehicles. It is reported that the emission leakages from transport refrigeration systems are higher than those from stationary refrigeration because the former operate under more severe conditions (IIR, 2003). The operating environment involves vibration, which will depend on road surface and a wide range of weather conditions and operating temperatures. Annual leakage figures reported are 10–37 percent of the refrigerant charge (IPCC/TEAP 2005). A study reported by Koehler et al. (2003), which assumed a 10 percent leakage rate showed the direct emissions (refrigerant leakage) from the refrigeration system to be 21 percent of indirect emissions (engine fuel consumption) for HFC-404A and 13 percent for HFC-410A.

Due to the country-specific variation in the amount of freight transported as well as the type of vehicles used (see UNECE 2010; Eurostat 2010; OECD 2010; USDOT 2010), GAINS derive HFC consumption per unit of freight transportation in 2005 based on the consumption reported by countries for this source to the UNFCCC. Figure S4 presents the HFC consumption in refrigerated transport sector per unit freight transportation in 2005 as reported by Annex-I countries to UNFCCC (2012). For countries not reporting HFC consumption specific for this sector, the rate reported for Austria (2.5 kg HFC per million tonne-km of freight transported) is adopted as default. Projections of HFC consumption in refrigerated transport follow proportionately growth in GDP (Capros et al., 2013; IEA/OECD, 2012). HCFC consumption in the refrigerated transport sector of China in 2009-10 and India in 2005 was 1.08 and 0.23 tonne HCFC per unit GDP, respectively (UNEP, 2011a; MoEF 2009). Due to the unavailability of HCFC consumption data for other developing countries, we adopt the Chinese and Indian value as default for HCFC consumption in the refrigerated transport sector of developing countries in general.

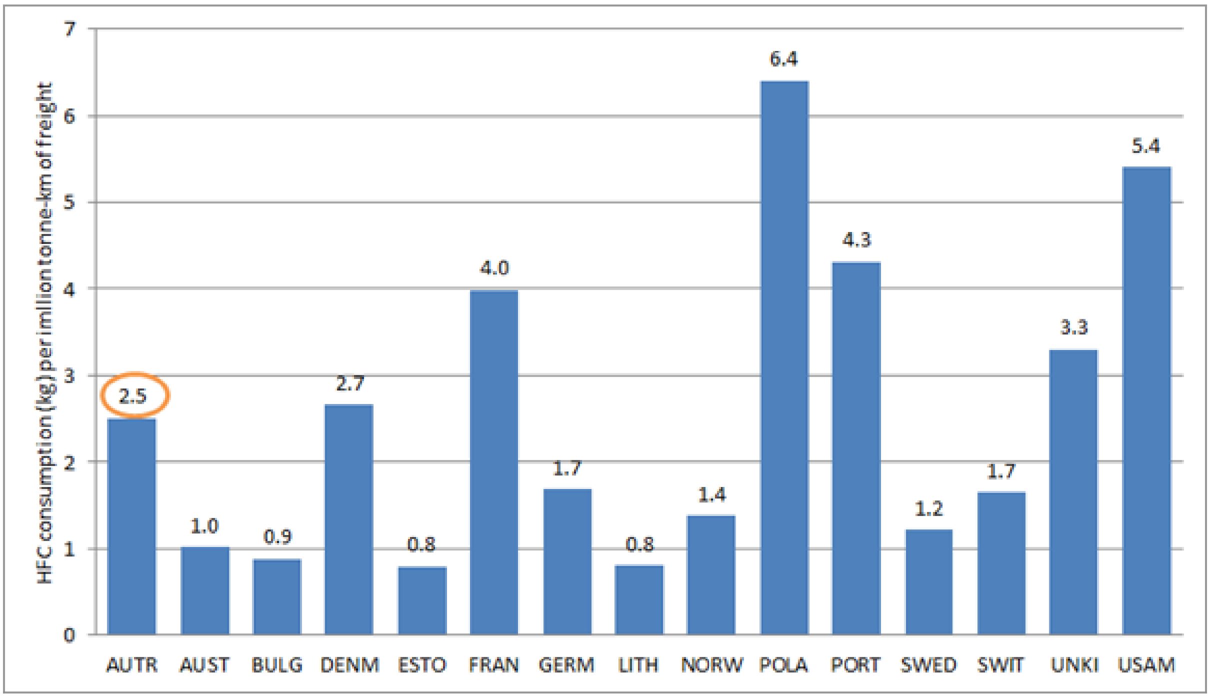

Figure S4. HFC consumption in refrigerated transport (in kg) per unit freight transportation (million tonne-km) in 2005 for Annex-I countries

Source: UNFCCC (2012)

An annual leakage rate of 25 percent for industrialized and 30 percent for developing countries (Gschrey et al., 2011) from refrigerated transport equipment in use is applied consistently across all GAINS regions. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery with recycling or destruction.

The control options available for this source are different good practice options including leakage control, improved components and end-of-life recollection. These options are assumed to remove 20 percent of emissions banked in equipment in use and 80 percent of scrapping emissions (Tohka, 2005). Further emission reductions from this source can be achieved through switches to alternative refrigerants like hydrocarbons (HC-290, HC-600a, etc.), CO_2 and NH_3. HFOs (i. e. HFO-1234yf blends) are also under consideration for use across transport refrigeration modes (USEPA, 2015).

S2.1.7 Mobile air-conditioning

A major source of F-gas emissions from the transport sector is emissions from mobile air-conditioners (MAC). Air conditioning in cars became common in the United States in the 1960s. Mass installation in Europe and developing countries started only later, around 1995. The refrigerant currently used in MACs is HFC-134a. The emissions of HFC-134a take place during accidents, through leakage and servicing and at disposal. Global recovery rates are generally low (DeAngelo et al. 2006), except for the EU where end-of-life recollection has been mandatory since 2000 due to the Directive on end-of-life vehicles (EC 53/2000).

In the GAINS model, emissions from MAC are accounted for in cars, light and heavy duty trucks, and buses. The number of vehicle types in different GAINS regions is extracted from the GAINS model and consistent with transport fuel use in respective external energy scenario. The penetration rates for air-conditioners in different vehicle types is extracted from a detailed literature review (Kanwar, 2004; Hu et al., 2004; IPCC/TEAP 2005; CSI 2009; Rhiemeier and Harnisch, 2009; Uherek et al. 2010; Henne et al., 2012; Yan et al. 2014; Su et al., 2015). Using the average charge size for different vehicle types the HFC consumption in the mobile air-conditioning sector is estimated (Repice and Schulz, 2004; IPCC/TEAP, 2005). Average charge sizes used are 0.6 kg for cars, 1.2 kg for light and heavy duty trucks and 12 kg for buses (Tohka, 2005; Schwarz et al., 2011). The leakage rate assumed from MAC in use is 10 percent (Tohka, 2005) and at the end-of-life the scrapped MAC is assumed to be fully loaded with coolant which needs recovery, recycling or destruction.

Following adherence to the MAC Directive-2006/40/EC, HFC-134a is expected to be replaced by a low GWP substance (GWP100 < 150) in all new models put on the market from January 2011 onwards. There are a few possible alternatives to HFC-134a including replacement with CO_2 (GWP_{100}=1), HFO-1234yf (GWP_{100}=4) or HFC-152a (GWP_{100}=124) (Yoo and Lee, 2009; Henne et al., 2012; Wang, 2014; Lee, 2015). However, the high system pressure and comparatively low efficiency of CO_2 and the flammability of HFC-152a make HFO-1234yf as the front runner of this race (Akasaka et al., 2010).

Evidence for mobile air conditioners from the B-COOL (2011) project funded by the EU Sixth Framework Program suggests that the cost of a CO_2-based AC system is between 1.5 to 2 times the costs of a HFC-134a system. Moreover, CO_2-based systems show slightly higher fuel consumption at higher thermal load (35 °C) as compared to the HFC-134a system. This is in contrast to the fuel (diesel/gasoline) savings claimed by some CO_2 promoters (e.g., www.r744.com). As a compromise we do not assume any effect on energy consumption when switching to a CO_2 based system in stationary or mobile air conditioners.

S2.1.8 Foams

Polyurethane one component foam (OC)

Foams became a significant application of HFCs as part of the phasing-out of CFCs under the MP. HFCs are used as blowing agents in a solidifying matrix of a polymer (UNEP, 2006). The main application of polyurethane (PU) one component (OC) foam is to fill cavities and joints when installing inner fixtures in housing constructions. Since one component foams come in pressurized canisters and cylinders, they are also called aerosol foams. One component blowing agents are typically gaseous and function as propellant for the foam. They volatilize upon application, except for small residues that remain for at most one year in the hardened foam. From early 2003, HFC-365mfc has been commercially produced as a substitute for foam blowing agent HCFC-141b, whose use in Europe has been banned since January 2004 (Stemmler et al., 2007).

To estimate emissions from one component foams we adopt HFC consumption in OC foams as reported by Annex-I countries to the UNFCCC (2012) for year 2005 and 2010. When reporting is missing for this source, the Swiss consumption per unit GDP (6.8 tonne HFC per billion Euro GDP) is adopted as default. Figure S5 presents the HFC consumption in one component foam sector per unit GDP in 2005 for Annex-I countries. HCFC consumption in OC foam sector of China and India in 2005 was 3.7 and 0.8 tonne HCFC per unit GDP, respectively (UNEP, 2011; MoEF 2009). Due to the unavailability of HCFC /HFC consumption data for other developing countries, we adopt the Chinese and Indian value as default for HCFC/HFC consumption in the refrigerated transport sector of developing countries in general. Projections of blowing agents for the one component foam sector follow growth in GDP (PRIMES baseline scenario (Capros et al., 2013; IEA/OECD, 2012).

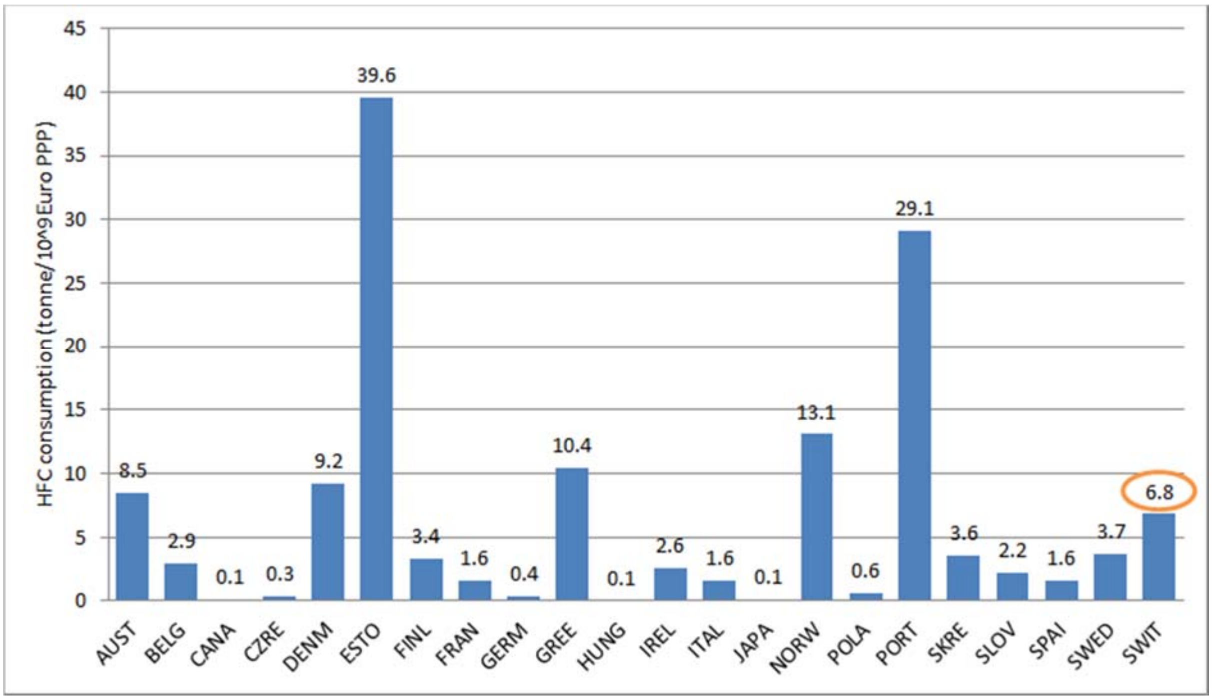

Figure S5. HFC consumption in one component foam sector per unit GDP in 2005 for Annex-I countries
Source: (UNFCCC 2012)

The annual release of HFCs from foams is assumed 15 percent of the stock banked in foams (UNFCCC, 2012; Höglund-Isaksson et al., 2013). Emissions from foams can be controlled by replacing HFC-134a and other high GWP blends (i. e. HFC-245fa, HFC-365mfc, etc.) with alternative low GWP blowing agents, like HFC-152a, hydrocarbons or CO_2. A recent mitigation option for applications where high pressure is essential is the replacement with HFO-1234ze (GWP_{100}=6) (Carvalho et al., 2014; Vollmer et al., 2015).

The EU F-gas Regulation requires that all EU member states from 2008 stop using HFCs in OC foam unless this is required to meet national safety standards. The most common current replacement options for HFCs in foams are hydrocarbons and CO_2. For some applications the performance of CO_2 in foam blowing is limited (UNEP, 2010). In GAINS, the options considered available for replacement of HFCs in one component foams are CO_2, different hydrocarbons like propane and butane, and HFO-1234ze.

Other foams (OF)

The sector for other foams (OF) in the GAINS model includes about 10 different polyurethane foam types (viz. 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 land filled, the emission factor depends mainly 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. To estimate emissions from the other foam sector we adopt HFC consumption in other foams as reported by Annex-I countries to the UNFCCC for years 2005 and 2010. For countries not reporting HFC consumption from this source, an average factor of 0.58 tonne HFC per billion Euro GDP is adopted as default. HCFC consumption in OC foam sector of China and India is taken from (UNEP, 2011) and (MoEF, 2009) respectively. Projections of refrigerants for one component foam sector follow GDP as taken from (Capros et al., 2013; IEA/WEO, 2012). The annual release of HFCs from foams is assumed 15 percent of the stock banked in foams (UNFCCC, 2012; Höglund-Isaksson et al., 2013).

Emissions from foams can be controlled by replacing HFC-134a and other high GWP blends with an alternative blowing agent like CO_2, water, hydrocarbons like propane or butane. According to Harvey (2007) a water/CO_2 mixture has been used in Europe (with a 10 to 20 percent market share by 2000) for solid PU in building applications. Approximately, 80 percent of XPS board foams in the EU use CO_2 for foam blowing however, CO_2 has some limitations with respect to thermal resistance and product thickness (UNEP, 2010). The remaining 20 percent will therefore need to use some other alternative, e.g., a mix of HFCs, HCs and water could be possible, but also HFO-1234ze is an interesting possible option (UNEP, 2010). In GAINS, the options considered available for replacement of HFCs in OF foams are CO_2, HFC-152a, different hydrocarbons like propane and butane, and HFO-1234ze.

S2.1.9 Aerosols

HFC is used as propellant for aerosols released from cans and metered dose inhalers, e.g., medical asthma inhalers. Following the MP, the use of CFCs as propellants in aerosol cans and metered dose inhalers (MDIs) are being replaced by other propellants. In the EU, the use of HFCs as propellant for aerosols in all applications for entertainment and decorative purposes has been prohibited since 2008 (Höglund-Isaksson et al., 2013). The release from this source is therefore mainly from MDIs, where high pressure is essential and the approval of new medical drugs is very expensive and time-consuming (UNEP, 2010; UNEP, 2015c). We assume that for the EU, the current use of HFCs in MDIs is limited to severe cases and that the primary gases used are HFC-134a with some use of HFC-152a. To estimate HFC consumption in aerosols, we adopt the HFC consumption reported by

Annex-I countries to the UNFCCC for years 2005 and 2010. According to this information the HFC use in aerosols in some countries is not exclusive to HFC-134a and HFC-227ea (GWP_{100}=3220). Instead, a certain fraction (20 percent in Canada, 68 percent in Japan, 14 percent Luxembourg and 2 percent in Hungary) refers to the use of other low GWP alternatives such as HFC-152a. Figure S6 presents the HFC consumption (t HFC/million people) in aerosol sector in 2005 for Annex-I countries. HFC consumption in aerosol sector of China and India is taken from (UNEP, 2011) and (MoEF, 2009) respectively. Population growth is used as driver for future HFC use in aerosols (EPC/DG ECFIN, 2012; IEA/OECD, 2012).

The primary alternatives to HFC-134a as propellant in MDI's are dry powder inhalers (DPI), hydrocarbons and HFC-152a (GWP_{100} = 140). The relative cost of these options is similar to the cost of MDIs in developed countries (UNEP, 2010), however, for medical reasons MDIs are still preferred in severe cases. For severe cases, where high pressure is essential, there is the option to replace HFC-134a with HFO-1234ze (GWP_{100} of 6), which according to the manufacturer Honeywell is already available for use as propellant for aerosols.

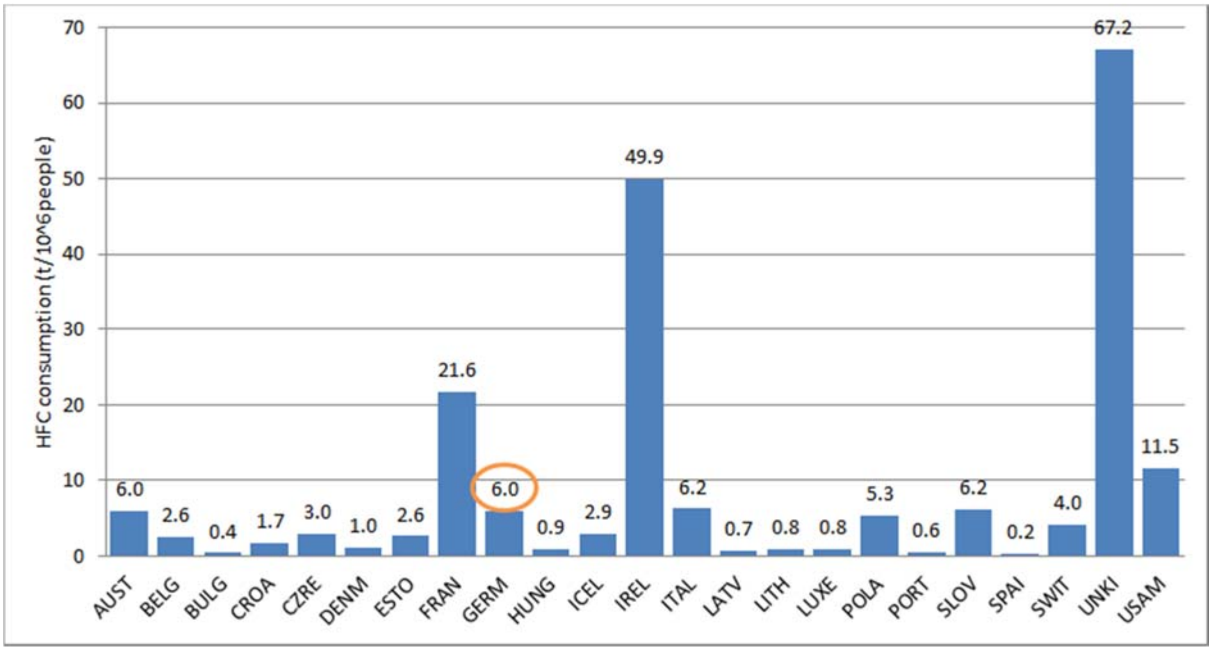

Figure S6. HFC consumption in aerosol sector (tonne/million people) in 2005

Source: (UNFCCC, 2012)

S2.1.10 HCFC-22 production

HCFC-22 (chlorodifluoromethane) is a hydrochloroflurocarbon (HCFC) used in refrigeration and air-conditioning systems, in foam manufacturing as a blend component of blowing agents, and in the manufacturing of synthetic polymers. Since it is an ODS its release is regulated in the MP. The phase-out schedule of HCFCs in the latest revision of the MP (UNEP, 2007) is presented in Table S3 for Article 5 (developing) and non-Article 5 (developed) countries. In addition to the phase-out of the use of HCFCs, the MP also requires the production and sales of HCFC-22 for emissive use to end completely by 2040.

In contrast to production of HCFC-22 for emissive use, the production and use of HCFC-22 as feedstock in industry is not regulated in the MP as it does not contribute to emissions of HCFCs. Production of HCFC-22 is however a source of HFC-23 emissions, which is a strong greenhouse gas with GWP$_{100}$ of 14,800 times that of CO$_2$ (IPCC, 1997). HCFC-22 production data is extracted from the Data Access Centre of the UNEP Ozone Secretariat (UNEP, 2013). HCFC-22 production for feedstock use in industry has increased significantly in Article-5 (developing) countries in the last decade. The market production of HCFC-22 in China increased from 106 kt in 2001 to 269 kt in 2005 with an average annual growth of 26.2 percent. HCFC-22 consumption for feedstock use increased with an average annual growth reaching 39.2 percent from 2001 to 2005 (Foroohar, 2007).

Table S3: Phase-out schedule of HCFCs for emissive use in the Montreal protocol

Year	Article 5 (developing) countries		Non-Article 5 (developed) countries	
	Pre 2007 revision of MP	Post 2007 revision of MP	Pre 2007 revision of MP	Post 2007 revision of MP
1996			Freeze in emissions	
2004			-35%	
2010			-65%	-75%
2013		Freeze in emissions*		
2015		-10%	-90%	-90%
2016	Freeze in emissions			
2020		-35%	-99.5%	-99.5%
2025		-67.5%		
2030		-97.5%	-100%	-100%
2035				
2040	-100%	-100%		

*at average of 2009 and 2010 level
Source: UNEP (2007)

To calculate HFC-23 emissions from HCFC-22 production, GAINS applies an IPCC default emission factor of 3 percent related to the volume of HCFC-22 production for emissive (HCFC22_E) and feedstock (HCFC22_F) applications (IPCC/TEAP, 2005). Activity data are based on reported production levels for historic years (UNEP, 2012) and UNEP's phase out schedule for HCFC products for future years (UNEP, 2007). Projections of HCFC-22 production for feedstock use are assumed to grow proportionately with value added in manufacturing industry.

HFC-23 emissions from HCFC-22 production can be almost eliminated through post combustion during which HFC-23 is oxidized to carbon dioxide, hydrogen fluoride (HF) and water. The marginal abatement cost for destruction of HFC-23 emissions from HCFC-22 production is very low, less than 1 Euro/tCO$_2$eq (Schneider 2011; IPCC/TEAP 2005). HFC-23 emissions from HCFC-22 production are assumed fully controlled in OECD countries through post-combustion. In this analysis we assume that the impact of CDM on emissions from HCFC-22 production in developing countries remain at the current level in the future (Fenhann, 2014).

S2.1.11 Ground source heat pumps

Geothermal energy is a renewable energy resource that can be used to provide electricity, heating, and cooling of commercial and domestic buildings and other facilities (IPCC, 2011). Geothermal heat pumps or ground source heat pumps (GSHP) are systems combining a heat pump with a ground heat exchanger (closed loop systems) or being fed by ground water from a well (open loop systems). The earth is used as a heat source when operated in heating mode, with a fluid as the medium which transfers the heat from the earth to the evaporator of the heat pump, thus utilizing geothermal energy (Sanner et al., 2003). In cooling mode, heat pumps use the earth as a heat sink. With borehole heat exchangers (BHE), geothermal heat pumps can offer both heating and cooling at virtually any location, with great flexibility to meet demands.

In Europe, the growth in GSHP systems has been accelerated by national policies stimulating installation, e.g., through subsidies, efficiency standards to new buildings and heating demand mandates for heat pumps (Eurobserver. 2009). Many European countries have identified barriers that mirror those seen in the United States, namely higher investment costs, lack of knowledge and awareness among end users, and underdeveloped institutional and financial support (EHPA, 2008). In the EU, Sweden (>320,000) and Germany (>150,000) today show the highest absolute numbers of GSHPs as shown in Figure S7.

Lund et al. (2011) estimated installed capacity of direct use geothermal in 2009 at 51 GW_{th}, distributed in 78 countries, while Goldstein et al. (2011) estimated direct use at 60 GW_{th} at the end of 2009. Direst use (ranging from 60 to 120°C) by type and relative estimates as given by Lund et al. (2011) were space heating (63%), bathing and balneology (25%), process heating and agricultural drying (3%), aquaculture (fish farming) (3%) and snow melting (1%). GSHP contributed to 70% (35.2 GWth) of the global installed geothermal heating capacity in 2009 (Ogola et al., 2012) and is the fastest growing of all forms of geothermal direct use since 1995 (Rybach 2005; Blum et al., 2010; Thorsteinsson and Tester, 2010; Yang et al., 2010; Heiskanen al., 2011; Lund et al. 2011; Schimschar et al. 2011). Although, most of the installations occur in North America, Europe, and China, the number of countries with installation increased from 33 in 2005 to 43 in 2010. The equivalent number of installed 12 kW units (typical of US and Western European homes) is approximately 2.76 million (Lund et al., 2011).

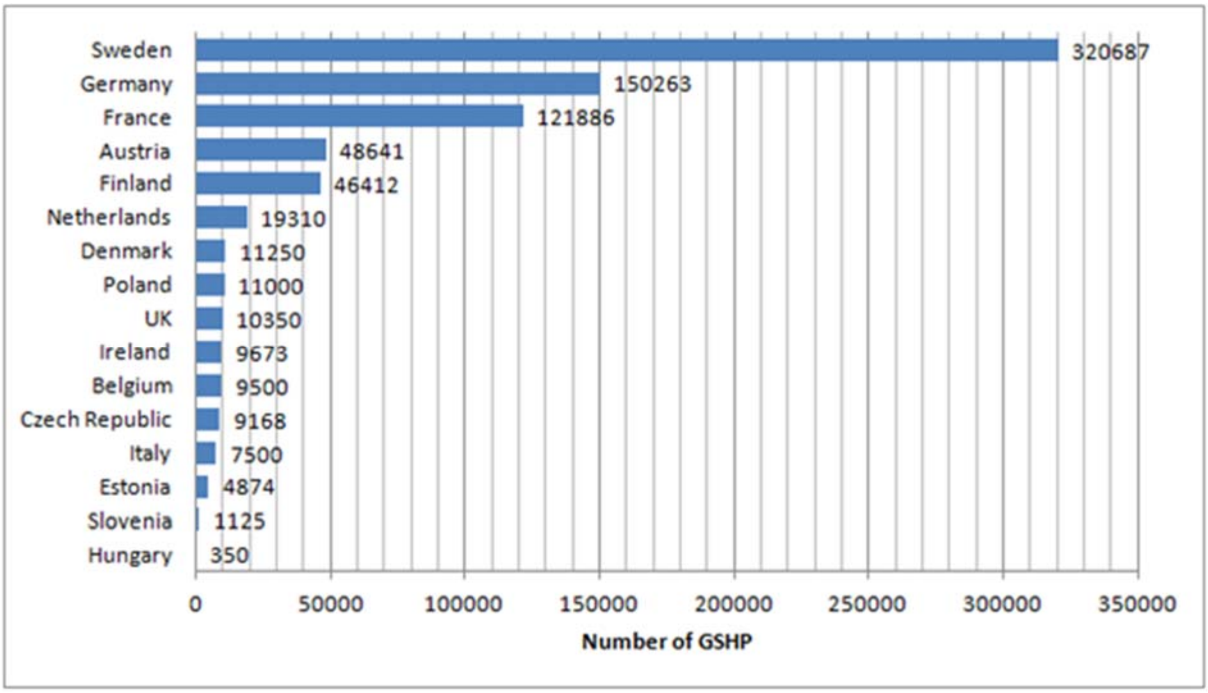

Figure S7: Number of existing GSHPs (with more than 10 MW heat capacity) in Europe
Source: EGEC (2009)

To estimate HFC consumption in the GSHP sector in the GAINS model we have taken the global GSHP installed capacity from Lund et al. (2005) and Lund et al. 2011), Eurobserv'er (2009), EHPA (2010) and Bayer et al. (2012). For projections, it is assumed that the annual growth in GSHPs using HFCs follows the growth of solar heating in the domestic sector as provided by the PRIMES model for EU-28 countries and IEA/OECD (2012) for non-EU-28 countries, but with the additional assumption that the market is saturated when the number of heat pumps corresponds to 20 percent of the number of households in a country. Growth in solar heating is here used as an approximation for the general growth in renewable energy sources. This is a rather crude assumption, which would be desirable to improve in the future through better information about the possibilities and limitations of expanding GSHP use in the different regions. Based on available technical information, the current fluid/refrigerant used in GSHP is most likely HFC-410A (IPCC/TEAP, 2005; Johnson, 2011) in Annex-I and HCFC-22 in non-Annex-I countries. An average refrigerant charge of 0.22 kg HFC per kW installed capacity (Schwartz et al., 2011) is used to estimate the HFC consumption in GSHP sector. Annual leakage from equipment is assumed 2.5 percent per year. Emissions can be controlled through good practice options and switching to alternative substances. . GAINS considers HC-290 direct, CO_2 and HFO-1234yf as a key alternatives for HFC-410A use in GSHP.

S2.1.12 Fire extinguishers

Fire extinguisher, or extinguisher, is an active fire protection device used to extinguish or control small fires, often in emergency situations. The extinguishing agent is stored in a container and released in case of fire. Unlike in the refrigeration and air conditioning sector, on site refilling and on site recycling do not take place. After intended release in the event of fire or in case the equipment is malfunctioning (leakage, pressure drop), the containers are returned to the manufacturers. Re-charging, repair work and recovery is always done off site by specialist personnel. As long as the extinguishing agent is contained, it does not get polluted by impurities, and reclamation is not relevant. The industry points out that recovery and recycling of F-gas fire extinguishing agents has been only carried out to a small extent, since HFCs in fire protection have only been in use since the mid-1990s. As the lifetime is 15 years or longer, most systems are still in use (Schwarz et al., 2011).

HFCs were not used in fire protection before the MP. Their current, and growing, usage is a direct result of their adoption as halon alternatives, despite being inferior to halons both in terms of cost and performance (IPCC/TEAP, 2005). To estimate HFC consumption in fire extinguishers, we derive consumption rates per unit of GDP using HFC consumption reported by Annex-I countries to UNFCCC (2012) for year 2005 and 2010 (see: Figure S8). In absence of data that could explain great fluctuations in this rate between countries, we adopt reported values when available and use the average factor of 0.68 ton per billion Euro GDP as a default factor for all countries for which reported consumption is missing. Projections of refrigerants for fire extinguishers sector follow GDP until 2050 as taken from the PRIMES baseline 2012 (Capros et al., 2013) for EU-28 and IEA/OECD (2012) for non-EU countries.

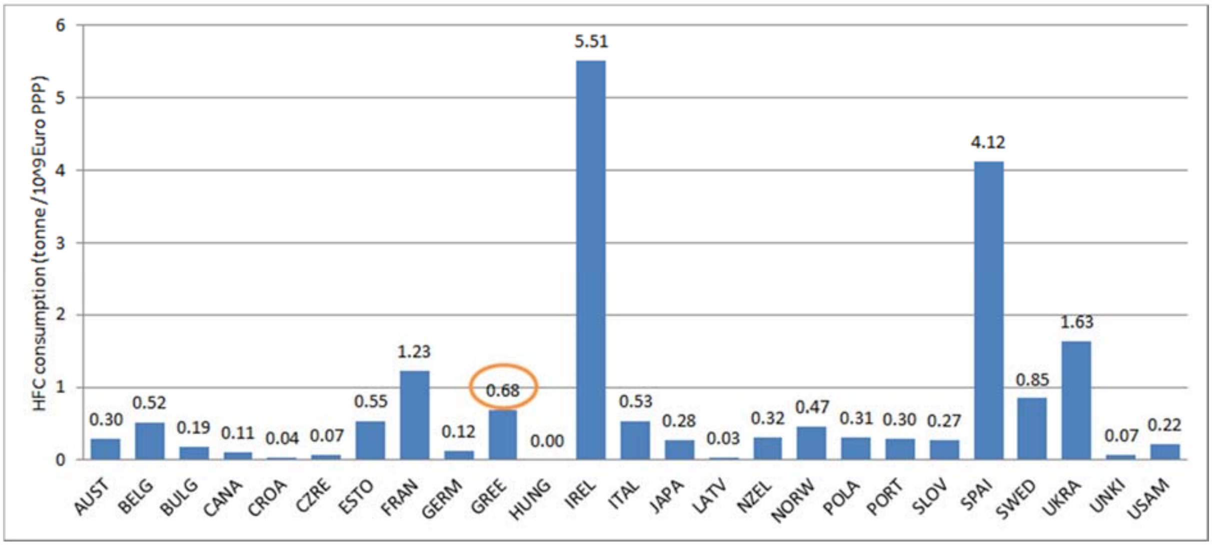

Figure S8. HFC consumption in fire extinguishers per unit GDP in 2005 for select countries

Source: UNFCCC (2012)

Figure S9 presents the share of HFC's and PFC's used in fire protection sector as reported by Annex-I countries for 2005 (UNFCCC, 2012). It is observed that HFC-227ea (54%), HFC-23 (23%), HFC-125 (13%) and HFC-236fa (7%) are mostly used for fire extinguishers in Annex-I countries. The majority of emissions will occur when the system is discharged, either when triggered accidentally or during a fire. Emissions may also occur during filling or maintenance of the systems; however these emissions are very small in newer systems, which often have leak detection and alarm systems as standard. Emissions are estimated to range from 1 to 3% of the fixed-system bank and 2 to 6% of the portable extinguisher bank per year (IPCC/TEAP, 2005). Annual leakage from equipment in GAINS is assumed 3.5 percent per year.

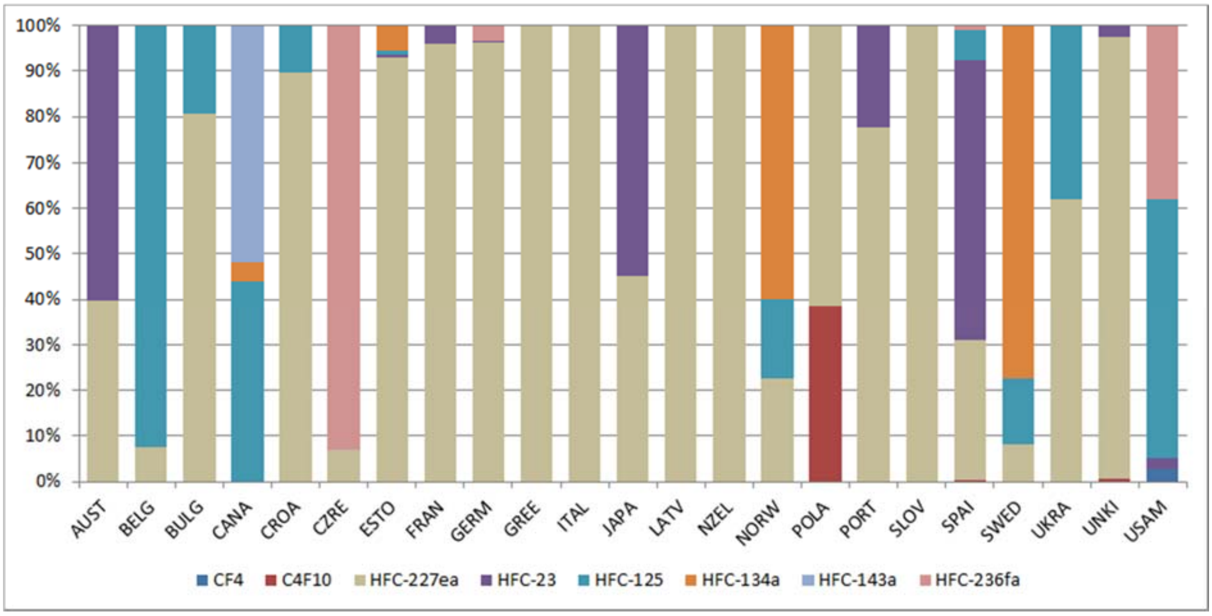

Figure S9. Share of HFC/PFC in fire protection sector of Annex-I countries in 2005

Emissions can be controlled through good practice options and switching to alternative substances. In recent years a low GWP alternative fluid (GWP_{100} = 1) with equivalent extinguishing properties had been introduced to the market with still growing success (Defra, 2008), the perfluoro-ketone FK 5-1-12 (Novec™ 1230). Its manufacturer and most European specialist equipment distributors rate FK 5-1-12 to be a feasible substitute for almost all applications of HFCs – for both HFC-227ea and HFC-23. GAINS considers FK-5-1-12 a key alternatives for HFC's in the fire extinguisher sector. In EU-28, fixed fire extinguisher systems are fully subject to the measures according to Art 3 and 4 of the F-gas Regulation. In developing countries, the Firefighting Sector phased out use of CFCs under the MP. The conversion technologies used were FM200, ABC powder, CO_2, etc. (MoEF, 2009).

S2.1.13 Solvents

F-gas based solvents are mainly used for degreasing of metal prior to precision coating and in the optics and electronics sector (Defra, 2008). Specific end-user sectors identified by March study (1999) include dry cleaning, metal cleaning, precision cleaning and electronics cleaning. In recent years, HFCs have been developed that are used for this application in sectors such as aerospace and electronics. CFCs were used as solvents in precision cleaning before being replaced by certain HCFCs, namely HCFC-141-b. As an ozone depleting substance, this HCFC has been replaced by HFC-43-10mee and HFC-c447ef. HFC-43-10mee has an atmospheric life of 15 years and GWP of 1,610 whereas HFC-c447ef has an atmospheric life of 4.3 years with GWP of 250 (IPCC/TEAP, 2005). The more recent HFCs coming onto the market are HFC-245fa and HFC-365mfc which were primarily introduced as foam blowing agents (IPCC/TEAP, 2005). New HFC species and replacements for this sector are Not-in-kind and in-kind alternatives to HCFC and HFC solvents.

To estimate HFC consumption in solvent sector, we adopt the HFC consumption reported by Annex-I countries to the UNFCCC for years 2005 and 2010. Five countries namely, Canada, Czech Republic, France, Switzerland and UK reported HFC consumption in solvent sector in their national communication to UNFCCC in 2005 (UNFCCC, 2012). At present, F-gas based solvents are not applied to a relevant extent with the exemption of France and UK in EU-28. Use of F-gas based solvents is prohibited in Denmark whereas F-gas solvents are not used in Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Ireland, Lithuania, Latvia, Malta, the Netherlands, Romania, Slovakia, Slovenia, and Sweden (Schwartz et al., 2011).

HFC consumption in solvent sector of China and India is taken from UNEP (2011) and MoEF (2009) respectively. Projections of refrigerants for solvents sector follow GDP until 2050 as taken from the PRIMES baseline 2012 scenario stored in the GAINS model for EU-28 and IEA/OECD (2012) for non-EU-28 countries.

Recovery for recycling or reclamation of F-gas based solvents is unlikely. Therefore, no further mitigation options beyond the ban on F-gas based solvents are considered necessary to control emissions from solvent sector in GAINS model.

S2.2 Perfluorocarbon compounds (PFC) emissions

There are two major sources for emissions of perfluorocarbon compounds (PFCs); primary aluminium (Al) production and the semiconductor industry. Emissions from these secto1rs have typically very high global warming potentials.

S2.2.1 Aluminium Industry

Primary Al production has been identified as a major emission source of the two PFCs tetrafluoromethane (CF_4) with GWP_{100} 7,390 and hexafluoroethane (C_2F_6) with GWP_{100} 12,200 times that of CO_2 (IPCC, 2007b). During normal operating conditions, an electrolytic cell used to produce aluminum 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 aluminum oxide drops too low and the electrolytic bath itself begins to undergo electrolysis. Since the aluminum 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 aluminum in the electrolytic bath is maintained at the correct level. The GAINS model uses the production volume of aluminum as the activity driver for calculating emissions from this source. Primary Al production data is taken from external data sources, i.e., from the PRIMES model for the EU countries and from U.S. Geological Survey (USGS, 2013) for non-EU countries. For China and India, primary Al production data is taken from the GAINS Asia project (Amann et al., 2008; Purohit et al., 2010). Four different types of activities are distinguished based on the technology used; point-feeder prebake (PFPB), side-worked prebake (SWPB), vertical stud söderberg (VSS), and center-worked prebake (CWPB) technology. Shares of different Al production technologies were adopted from the Al industry websites, national communications to the UNFCCC (2012) and other publically available literature (Schwarz, 2008; RUSAL. 2009; IAI, 2009; Schwarz et al., 2011; Marks and Rand, 2012; IAI, 2014).

Emission factors depend on the production technology and on a number of site-specific conditions and are taken from Harnisch and Hendricks (2000). Chinese Al production was dominated by Horizontal Stud Soderberg (HSS) technology until the mid-2000s, but through the mid-2000s a transformation occurred and by the end of 2005 the China Non-Ferrous Metals Industry Association (CNIA) reported 100 percent use of PFPB technology. The International Aluminium Institute (IAI) observed a median PFPB emission factor for 8 Chinese smelters 2.6 times larger than the global PFPB technology average (IAI, 2009). Assuming the Chinese EF is constant in time (Mühle et al., 2010) the revised CF_4 emissions factor for Chinese Al smelters is used in this study. Conversion of SWPB, VSS or CWPB technology to PFPB technology removes over 90 percent of PFC emissions, while retrofitting of the three technologies would remove about a quarter of emissions (Harnisch and Hendricks, 2000). Data on mitigation costs is taken from the same source. In Europe, emissions from the primary Al production is regulated under the EU-ETS system, control options with marginal costs falling below the expected ETS carbon price are adopted in the reference scenario. This means that with the natural turn-over of capital, all EU member states will have phased-in PFPB technology by 2020.

The development of inert anodes is sometimes promoted as a promising mitigation option, which could eliminate emissions of PFCs from the electrolysis process (IPCC, 2007a; Kvande and Drabløs, 2014). In the Energy Technology Perspective (ETP) 2010 by the International Energy Agency (IEA/OECD, 2010), deployment of inert anode technologies is expected to start in 2015-2020 with full commercialization by 2030 (Table S4). If realized, inert anode technology would have significant energy, cost, productivity, and environmental benefits for the aluminum industry worldwide (RUSAL, 2010). The technology is expected to eliminate PFC emissions from primary Al production altogether. Despite promising initial results, the technology still needs further development before it can be introduced as a viable alternative to PFPB technology. In GAINS, inert anode technology is assumed available as a mitigation option from 2035 onwards, however, no adoption in the reference scenario is assumed.

Table S4. Technology options for the aluminium industry

Technology	R&D needs	Demonstration needs	Deployment milestones
Wetted drained cathodes	-	Ready for demonstration	Deployment to start by 2015 with full commercialization by 2020
Inert anodes	Extensive testing at laboratory and batch scale	Ready to be demonstrated at plant level	Deployment to start in 2015-2020 with full commercialization by 2030
Carbothermic reduction	Extensive research under way	2020 - 2025	Deployment to start between 2030 and 2040 with full commercialization by 2050
Kaolinite reduction	Research under way	2025 - 2030	Deployment to start between 2035 and 2045

Source: (IEA/OECD, 2010)

S2.2.2 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-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 (IPCC, 2001). Because PFC is only used by few companies in a country (Tohka, 2005) and because the amount of PFC use allows deriving production volumes, data on PFC use are often confidential. As activity variables for this sector GAINS uses the volume of PFC emissions as reported by Annex-I countries to UNFCCC (2012). For countries not reporting PFC consumption in this sector, the Chinese consumption rate of 6.4 Gg PFC per billion Euro value added in manufacturing sector (Bartos et al., 2008) in 2005 has been adopted as default.

S2.3 Sulphur hexafluoride (SF_6) emissions

Sulphur hexafluoride emissions arise from high and mid-voltage switches, magnesium production and casting, soundproof glazing and a variety of other applications using SF_6. Compared to anthropogenic sources, natural sources of SF_6 are negligible. Although the atmospheric concentration of SF_6 is relatively low, contributing 0.1% of the total anthropogenic radiative forcing, the concentration is growing continuously (Levin et al., 2010; Rigby, et al. 2010) because of the compound's long lifetime of~3200 years (Ravishankara et al., 1993).

S2.3.1 High and mid voltage switches

The electrical equipment sector is the major emission source of SF_6 through leakage, maintenance, and retiring (IPCC/TEAP, 2005). SF_6 is used as an electrical insulator in the transmission and distribution equipment of electric systems. Most of the SF_6 is stored in gas-insulated switchgears for high and mid-voltage electric networks. Emissions of SF_6 depend on the age of the gas insulated switchgear since older models leak more than newer ones, as well as on the size of the transmission network and on recycling practices of the old equipment. The GAINS model uses electricity consumption as activity variable for this sector. The emission factor for SF_6 in electricity transmission per unit of electricity consumed is taken from the GHG inventory of California (CEPA, 2010) and applied in a consistent manner to all regions.

Suitable alternatives to SF_6 do not exist for these applications as the oil and compressed air systems, which were used previously, suffer from safety and reliability problems (AEAT, 2003). SF_6 emissions resulting from leaks in electrical equipment can be addressed through leak detection and repair (LDAR) and, for larger leaks, refurbishment. SF_6 emissions can be reduced through the adoption of recycling practices of used SF_6 switchgears. The EU F-gas Regulation requires end-of-life recollection and recycling from 2010 onwards. Full compliance with this regulation is assumed in GAINS to apply in all EU countries.

S2.3.2 Magnesium production and magnesium casting

Casting and production of primary and secondary magnesium are well known sources of atmospheric emissions of SF_6. The gas 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 (IPCC, 2001). Activity data on historic volumes of processed magnesium are taken from the United States Geological Survey (USGS, 2013), UN statistics and the national communications to UNFCCC (UNFCCC, 2012). An emission factor of 1 kg SF_6 per ton processed metal is taken from Schwartz and Leisewitz (1999) and Tohka (2005). Based on the recently published data, magnesium processing SF_6 consumption factors of 1.65 kg SF_6/t Mg is used for China (Fang et al., 2013). SF_6 emissions in magnesium production and casting can be substituted by using sulphur dioxide (SO_2) as alternative gas.

S2.3.3 Soundproof windows

Some European countries used significant amounts of SF_6 in soundproof windows. From 2006, the F-gas Regulation bans the use of SF_6 soundproof windows. Soundproof windows have a relatively long life-time and it is therefore expected that the stock of SF_6 found in such windows in 2005 will be successively phased-out over a period of 25 years. The available stock of SF_6 in soundproof windows in 2005 in EU countries is estimated at 288 t SF_6 in Austria, 75 t SF_6 in Belgium, 86 t SF_6 in Denmark, 1764 t SF_6 in Germany, 1.78 t SF_6 in Slovenia, and

11.1 t SF_6 in Sweden (Hoglund-Isaksson et al., 2013). These estimates were verified in national communications between IIASA and country experts as part of review processes of baseline non-CO_2 GHGs organized by the European Commission in 2009 and 2012. With an assumed leakage/refill rate of 1 percent per year for windows still in use and a linear phase-out of emissions, annual emissions from this source until 2030 (when phase-out is completed) are estimated as:

$$E_t^{SF_6} = \frac{Stock_{2005}}{25} + Stock_t \; * 0.01 \qquad (6)$$

where the first term represents the end-of-life emissions from soundproof windows scrapped in year t and the latter term represents the emission leakage from windows still in use.

No further mitigation options beyond the ban included in the F-gas Regulation are considered necessary to control emissions from soundproof windows.

S2.3.4 Other applications

SF_6 have been used in tyres, sports equipment manufacturers in tennis balls and sport shoes. Activity data for these other sources of SF_6 emissions in Annex-I countries are taken from emissions reported by countries to the UNFCCC (2012). From 2006, the F-gas Regulation bans the use of SF_6 in sports equipment and tyres in EU-28. GAINS assumes all EU-28 countries adhere fully to this ban. For developing countries, information on SF_6 consumption in other applications is missing.

Table S5. GAINS F-gas emission sources, activity data and drivers

S.No.	Emission source	Historical activity data	Projection driver
A.	**HFC emissions**		
1	Aerosols	HCFC/HFC consumption for MDI's and other aerosols (MoEF, 2009; UNEP, 2011; UNFCCC, 2012)	Growth in population from PRIMES (2012) for EU-28 and IEA/OECD (2012) for non-EU-28 countries
2	Commercial air conditioning	GDP and population (PRIMES, 2012; IEA/OECD, 2012), household size (UN-Habitat 2005), cooling degree days (Baumert and Selman, 2003), commercial floor space (Cofala et al., 2009), refrigerant charge (Höglund-Isaksson et al. 2013)	Growth in GDP and population from PRIMES (2012) for EU-28 and IEA/OECD (2012) for non-EU-28 countries
3	Commercial refrigeration	HCFC/HFC consumption in the commercial sector (MoEF, 2009; UNEP, 2011; UNFCCC, 2012)	Growth in commercial value added from PRIMES (2012) for EU-28 and IEA/OECD (2012) for non-EU-28 countries
4	Domestic small hermetic refrigerators	GDP and population (IEA/OECD, 2012), household size (UN-Habitat 2005), urbanization and electrification rate (IEA-WEO Reports, National Census and World Bank surveys)	Growth in GDP and population from PRIMES (2012) for EU-28 and IEA/OECD (2012) for non-EU-28 countries
5	Fire extinguishers	HCFC/HFC consumption in fire extinguishers (MoEF, 2009; UNEP, 2011; UNFCCC, 2012)	Growth in GDP from PRIMES (2012) for EU-28 and IEA/OECD (2012) for non-EU-28 countries
6	Ground source heat pumps*	Geothermal (direct-use) data (Lund et al., 2011), specific refrigerant charge (Schwartz et al. 2011)	Growth in solar thermal energy use in residential sector from PRIMES (2012) and IEA/OECD (2012).
7	HCFC-22 production for emissive use	HCFC production (UNEP, 2012)	Growth in industrial value added from PRIMES (2012) for EU-28 and IEA/OECD (2012) for non-EU-28 countries
8	HCFC-22 production for feedstock use	HCFC production (UNEP, 2012; IPCC, 2006)	Growth in industrial value added from PRIMES (2012) for EU-28 and IEA/OECD (2012) for non-EU-28 countries
9	Industrial refrigeration	HCFC/HFC consumption in industrial refrigeration (MoEF, 2009; UNEP, 2011; UNFCCC, 2012)	Growth in industrial value added from PRIMES (2012) for EU-28 and IEA/OECD (2012) for non-EU-28 countries
10	Mobile air conditioning	Number of vehicles (cars, buses, light and heavy duty trucks) with air conditioning (GAINS model; Tohka, 2005; Höglund-Isaksson et al., 2009).	Growth in vehicles numbers from GAINS model and penetration of MAC from (Tohka, 2005; Höglund-Isakssonet al., 2009)
11	Foam	HCFC/HFC consumption in the foam sector (MoEF, 2009; UNEP, 2011; UNFCCC, 2012)	Growth in GDP from PRIMES (2012) for EU-28 and IEA/OECD (2012) for non-EU-28 countries
12	Residential air conditioning	GDP and population (PRIMES, 2012; IEA/OECD, 2012), household size (UN-Habitat 2005), cooling degree days (Baumert and Selman, 2003), refrigerant charge (Höglund-Isaksson et al. 2013)	Growth in GDP and population from PRIMES (2012) for EU-28 and IEA/OECD (2012) for non-EU-28 countries

13	Refrigerated transport	HCFC/HFC consumption in refrigerated transport sector (MoEF, 2009; UNEP, 2011; UNFCCC, 2012)	Growth in GDP from PRIMES (2012) for EU-28 and IEA/OECD (2012) for non-EU-28 countries
14	Solvents	HCFC/HFC consumption in solvents (MoEF, 2009; UNEP, 2011; UNFCCC, 2012)	Growth in GDP from PRIMES (2012) for EU-28 and IEA/OECD (2012) for non-EU-28 countries
B. PFC emissions			
15	Primary Al production	Primary Al production data from PRIMES model, U.S. Geological Survey and GAINS Asia Project.	Energy consumption in non-ferrous metals from IEA/OECD (2012)
16	Semiconductor industry	PFC emissions in semiconductor industry (Bartos et al., 2008; UNFCCC, 2012)	Growth in industrial value added from IEA/OECD (2012)
C. SF_6 emissions			
17	High and mid voltage switches	Electricity consumption (GAINS model)	Electricity consumption from IEA/OECD (2012)
18	Magnesium production and magnesium casting	Magnesium production data from PRIMES Model for EU-28; GAINS model and U.S. Geological Survey for non-EU regions.	Energy consumption in non-ferrous metals from IEA/OECD (2012)
19	Soundproof windows	SF_6 emissions from soundproof windows (Höglund-Isaksson et al., 2010).	GDP growth from IEA/OECD (2012)
20	Other SF_6 emissions	Other SF_6 emissions from (UNFCCC, 2012)	GDP growth from IEA/OECD (2012)

**For regions without solar thermal/renewable use in residential sector growth in GDP is considered as a projection driver.*

Table S6. Mitigation options for HFC emissions considered in the GAINS model

Sector description	**Technology description**	**Unit of activity data**	**Removal efficiency**	**Cost parameters per unit of activity data**				
				Lifetime of equipment	Investment	Operation & maintenance	Electricity demand	Labour time
				years	million €	million €/year	GWh	fraction of annual work hrs (1800 hrs)
Aerosols	Alternative hydrocarbon propellant (i. e. propane (HC-290), iso-butane (HC-600a), n-propane etc.)	kt HFC	-99.79%	0	0	-2	0	0
	Alternative propellant (i. e. HFC-152a)		-91.33%	0	0	-1	0	0
	Alternative propellant (e. g. HFO-1234ze)		-99.58%	0	0	9.29	0	0
Commercial air conditioning, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-30%	10	0	1.44	0	0.000088
	Alternative hydrocarbon refrigerant (i. e. propane, iso-butane, propene (HC-1270), etc.)		-99.85%	20	34.86	-1.91	0	0
	Alternative technology: pressurized CO_2		-99.95%	10	112.78	2.97	200	0
	Alternative low-GWP HFC's (e. g. HFC-152a)		-93.81%	10	138.27	-0.71	0	0
	Alternative low GWP refrigerant (i. e. HFO-1234yf)		-99.80%	10	169.17	2.25	0	0
Commercial air conditioning, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-88%	10	0	33.33	0	0
	Alternative hydrocarbon refrigerant (i. e. propane, iso-butane, propene, etc.)		-99.85%	0	0	0	0	0
	Alternative technology: pressurized CO_2		-99.95%	10	0	0	0	0
	Alternative low-GWP HFC's (e. g. HFC-152a)		-93.81%	10	0	16.67	0	0
	Alternative low GWP refrigerant (i. e. HFO-1234yf)		-99.80%	10	0	16.67	0	0
Commercial refrigeration, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-33%	10	0	2.75	0	0.000121
	Alternative hydrocarbon refrigerants (i. e. propane, iso-butane, propene, etc.)		-99.91%	10	913.51	-0.89	-0.00025	0
	Alternative low-GWP HFC's (e. g. HFC-152a)		-96.13%	10	136.87	-12.75	0	0
	Alternative technology: pressurized CO_2		-99.97%	10	230.98	-7.47	300	0
Commercial refrigeration, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	10	0	1.16	0	0
	Alternative hydrocarbon refrigerants (i. e. propane, iso-butane, propene, etc.)		-99.91%	0	0	0	0	0
	Alternative low-GWP HFC's (e. g. HFC-152a)		-96.13%	10	136.87	-12.75	0	0
	Alternative technology: pressurized CO_2		-99.97%	10	0	0	0	0
Domestic small hermetic refrigerators, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	15	0	12.5	0	0
	Alternative hydrocarbon refrigerant (i. e. iso-butane)		-99.79%	15	92.65	-4.42	0	0
Fire extinguishers, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-20%	20	0	0.53	0	0.000007
	Alternative agent: Fluoro-ketone (FK-5-1-12)		-100%	20	25.88	0.37	0	0
Fire extinguishers, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-90%	20	0	0.8	0	0
	Alternative agent: Fluoro-ketone (FK-5-1-12)		-100%	20	0	0.61	0	0
Ground source heat pumps, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-30%	15	0	0.36	0	0.000116
	Alternative hydrocarbon refrigerants (i. e. Propane (HC-290), propene (HC-1270), etc.)		-99.86%	15	134.35	-0.35	0	0
	Alternative technology: pressurized CO_2		-99.95%	15	338.18	-0.3	50	0
	Alternative low-GWP HFC's (e. g. HFC-152a)		-94.06%	15	171.41	1.31	0	0
Ground source heat pumps, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	15	0	20.8	0	0
	Alternative hydrocarbon refrigerants (i. e. Propane (HC-290), propene (HC-1270), etc.)		-99.86%	15	0	20.83	0	0
	Alternative technology: pressurized CO_2		-99.95%	15	0	0	0	0
	Alternative low-GWP HFC's (e. g. HFC-152a)		-94.06%	15	0	20.83	0	0
HCFC-22 production for emissive use	Post combustion of HFC-23	kt HFC	-99.99%	10	16.46	2.19	0	0
HCFC-22 production for feedstock use	Post combustion of HFC-23		-99.99%	10	16.46	2.19	0	0

Continued Table S6. Mitigation options for HFC emissions considered in the GAINS model

Sector description	Technology description	Unit of activity data	Removal efficiency	Cost parameters per unit of activity data				
				Lifetime of equipment years	Investment million €	Operation & maintenance million €/year	Electricity demand GWh	Labour time fraction of annual work hrs (1800 hrs)
Industrial refrigeration (including food and agricultural sectors), emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-42%	15	0	1.43	0	0.000008
	Alternative refrigerant: Propane (HC-290)		-99.88%	10	913.51	-0.89	-0.00025	0
	Alternative low-GWP HFC’s (e. g. HFC-152a)		-95.01%	15	136.87	-12.75	0	0
	Alternative refrigerant: ammonia (NH_3)		-100%	15	468.09	-48.05	-337.5	0
	Alternative technology: pressurized CO_2		-99.96%	15	133.64	-5.88	69	0
Industrial refrigeration (including food and agricultural sectors), emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-88%	15	0	0.18	0	0
	Alternative refrigerant: Propane (HC-290)		-99.88%	0	0	0	0	0
	Alternative low-GWP HFC’s (e. g. HFC-152a)		-95.01%	15	136.87	-12.75	0	0
	Alternative refrigerant: ammonia (NH_3)		-100%	15	468.09	0	0	0
	Alternative technology: pressurized CO_2		-99.96%	15	0	0	0	0
Mobile air-conditioner in buses, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-50%	12	0	1	0	0
	Alternative refrigerant: HFO-1234yf		-99.72%	12	68.63	6.73	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	193.41	3.17	0	0
Mobile air-conditioner in buses, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	12	0	0	0	0.0000042
	Alternative refrigerant: HFO-1234yf		-99.72%	12	17.36	0	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	0	0	0	0
Mobile air-conditioner in heavy duty trucks, emissions banked in equipment	Good practice: end-of-life recollection	kt HFC	-50%	12	0	0.5	0	0
	Alternative refrigerant: HFO-1234yf		-99.72%	12	48.67	5	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	56.78	-2	0	0
Mobile air-conditioner in heavy duty trucks, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	12	0	0	0	0.0000187
	Alternative refrigerant: HFO-1234yf		-99.72%	12	17.36	0	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	0	0	0	0
Mobile air-conditioner in cars, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-50%	12	0	0.5	0	0
	Alternative refrigerant: HFO-1234yf		-99.72%	12	48.67	6.92	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	170	-0.08	0	0
Mobile air-conditioner in cars, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	12	0	0	0	0.0000373
	Alternative refrigerant: HFO-1234yf		-99.72%	12	17.36	0	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	0	0	0	0
Mobile air-conditioner in light duty trucks, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-50%	12	0	0.5	0	0
	Alternative refrigerant: HFO-1234yf		-99.72%	12	48.67	5	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	56.78	-2	0	0
Mobile air-conditioner in light duty trucks, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	12	0	0	0	0.0000373
	Alternative refrigerant: HFO-1234yf		-99.72%	12	17.36	0	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	0	0	0	0

Continued Table S6. Mitigation options for HFC emissions considered in the GAINS model

Sector description	**Technology description**	**Unit of activity data**	**Removal efficiency**	**Cost parameters per unit of activity data**				
				Lifetime of equipment years	Investment million €	Operation & maintenance million €/year	Electricity demand GWh	Labour time fraction of annual work hrs (1800 hrs)
One component foams	Alternative hydrocarbon blowing agents (i. e. Iso-butane (HC-600a), Iso-pentane, n-pentane, etc.)	kt HFC	-99.74%	15	1.74	0	0	0
	Alternative technology: pressurized CO_2		-99.91%	15	6.96	-1	0	0
	Alternative blowing agent: HFO-1234ze		-99.47%	15	3.48	7	0	0
	Alternative low-GWP HFC's (e. g. HFC-152a)		-89.13%	15	1.74	-3	0	0
Other foams	Alternative hydrocarbon blowing agents (i. e. Iso-butane (HC-600a), Iso-pentane, n-pentane, etc.)	kt HFC	-99.74%	15	1.74	0	0	0
	Alternative technology: pressurized CO_2		-99.91%	15	6.96	-1	0	0
	Alternative blowing agent: HFO-1234ze		-99.47%	15	3.48	7	0	0
	Alternative low-GWP HFC's (e. g. HFC-152a)		-89.13%	15	1.74	-3	0	0
Other HFC use	Alternative low-GWP HFC's (e. g. HFC-152a)	kt HFC	-91.33%	0	0	2	0	0
Refrigerated transport, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-20%	15	0	2.5	0	0.0000427
	Alternative hydrocarbon refrigerant: Propane (HC-290), propene (HC-1270)		-93.45%	15	136.87	-12.75	0	0
	Alternative technology: pressurized CO_2		-99.95%	15	403.68	-41.88	0	0
	Alternative low-GWP HFC's (e. g. HFC-152a)		-93.45%	15	136.87	-12.75	0	0
Refrigerated transport, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	15	0	0	0	0.0000427
	Alternative hydrocarbon refrigerant: Propane (HC-290), propene (HC-1270)		-99.84%	0	0	0	0	0
	Alternative technology: pressurized CO_2		-99.95%	15	0	0	0	0
	Alternative low-GWP HFC's (e. g. HFC-152a)		-93.45%	15	136.87	-12.75	0	0
Residential air conditioning, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-30%	10	0	1.44	0	0.000088
	Alternative hydrocarbon refrigerant (i. e. propane (HC-290), iso-butane (HC-600a), propene (HC-1270), etc.)		-99.85%	10	-7.46	-1.49	-0.00037	0
	Alternative technology: pressurized CO_2		-99.95%	10	116.8	0.78	200	0
	Alternative low-GWP HFC's (e. g. HFC-152a)		-93.81%	10	-20.01	-0.6	0	0
	Alternative low GWP refrigerant (i. e. HFO-1234yf)		-99.80%	10	87.60	2.27	0	0
Residential air conditioning, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-88%	10	0	33.33	0	0
	Alternative hydrocarbon refrigerant (i. e. propane (HC-290), iso-butane (HC-600a), propene (HC-1270), etc.)		-99.85%	0	0	0	0	0
	Alternative technology: pressurized CO_2		-99.95%	10	0	0	0	0
	Alternative low-GWP HFC's (e. g. HFC-152a)		-93.81%	10	0	33.33	0	0
	Alternative low GWP refrigerant (i. e. HFO-1234yf)		-99.80%	10	0	33.33	0	0
Solvents	Ban of use	kt HFC	-100%	0	0	1	0	0

Source: (IPCC/TEAP, 2005; Tohka, 2005; Schwartz et al., 2011; Höglund-Isaksson et al., 2012; Höglund-Isaksson et al., 2013; USEPA, 2013; Purohit et al, 2016)

Table S7. Mitigation options for PFC and SF_6 emissions considered in the global version of the GAINS model

Sector description	Technology description	Unit of activity data	Removal efficiency	Cost parameters per unit of activity data				
				Lifetime of equipment	Investment	Operation & maintenance	Electricity demand	Labour time
				years	million €	million €/year	GWh	fraction of annual
A. PFC Emissions								
Primary Al production with Centre worked prebake (CWPB) technology	CWPB to PFPB conversion	Mt primary Al	-85%	20	150	-2.13	-1700	0
	CWPB to NEW[*] conversion		-100%	20	3045	0	0	0
	CWPB retrofitting		-26%	20	40	0	0	0
Primary Al production with point feeder prebake (PFPB) technology	PFPB to NEW conversion	Mt primary Al	-100%	20	3150	0	0	0
Primary Al production with side worked prebake (SWPB) technology	SWPB to PFPB conversion	Mt primary Al	-97%	20	700	-9.94	-800	0
	SWPB to NEW conversion		-100%	20	2660	0	0	0
	SWPB retrofitting		-26%	20	77.78	0	0	0
Primary Al production with vertical stud Söderberg (VSS) technology	VSS to PFPB conversion	Mt primary Al	-92%	20	3250	-46.15	-2300	0
	VSS to NEW conversion		-100%	20	875	0	0	0
	VSS retrofitting		-28.19%	20	175	-7	0	0
Semiconductor manufacture	Alternative solvent: use of NF_3	kt PFC	-99%	0	0	183.54	0	0
B. SF_6 Emissions								
SF_6 consumption in high and mid voltage switches	Good practice: leakage control and end-of-life recollection and recycling	kt SF_6	-84%	0	0	86.04	0	0
Magnesium production and magnesium casting	Alternative protection gas: SF_6 replaced by SO_2	t Mg processed	-100%	1	9.12	0.0456	0	0
Soundproof windows	Ban of use	kt SF_6	-100%	0	0	2.62	0	0
Other SF_6 emission sources	Ban of use	kt SF_6	-100%	0	0	2.62	0	0

[*] NEW refer to Wetted drained cathodes, Inert anodes, Carbothermic reduction and Kaolinite reduction as mentioned in IEA's Energy Technology Perspective 2010 (IEA/OECD, 2010)

Table S8. Regional aggregations of F-gas emission estimates in GAINS

World region	GAINS F-gas regions
Africa	Egypt, South Africa, North Africa (includes Algeria, Morocco, Libya, Tunisia, Sudan), and Other Africa (includes all other African countries)
Australia & New Zealand	Australia and New Zealand
China	Anhui, Beijing, Chongqing, Fujian, Gansu, Guangdong, Guangxi, Guizhou, Hainan, Hebei, Heilongjiang, Henan, Hong Kong & Macau, Hubei, Hunan, Jilin, Jiangsu, Jiangxi, Liaoning, Inner Mongolia, Ningxia, Qinghai, Shaanxi, Shanghai, Shandong, Shanxi, Sichuan, Tianjin, Tibet (Xizang), Xinjiang, Yunnan, Zhejiang
India	Andhra Pradesh, Assam, West Bengal, Bihar, Chhattisgarh, Delhi, North East-(excl. Assam), Goa, Gujarat, Haryana, Himachal Pradesh, Jharkhand, Karnataka, Kerala, Maharashtra, Madhya Pradesh, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttaranchal, Uttar Pradesh, Jammu and Kashmir
Asia rest	Afghanistan, Armenia, Azerbaijan, Bangladesh (two regions), Bhutan, Brunei, Cambodia, Former Soviet Union States (includes Tajikistan, Turkmenistan and Uzbekistan), Georgia, Indonesia (4 regions), Japan (Chugoku-Shikoku, Chubu, Hokkaido-Tohoku, Kanto, Kinki, Kyushu-Okinawa), Kazakhstan, Kirgizstan, Nepal, North Korea, Laos, Malaysia (Kuala Lumpur, Peninsular Malaysia, Sarawak-Sabah), Mongolia, Myanmar, Pakistan (Karachi, North-West Frontier Provinces and Baluchistan, Punjab, Sind), Philippines (Bicol-Visayas-Mindanao, Luzon, Metro Manila), Singapore, South Korea (North, Pusan, Seoul-Inchon, South), Sri Lanka, Taiwan, Thailand (Bangkok Metropolitan Region, Central Valley, N Highlands, NE Plateau, S Peninsula) and Vietnam
EU-28	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom
Middle East	Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen
Latin America	Argentine, Brazil, Chile, Mexico, Other Latin America
Europe rest	Albania, Belarus, Iceland, Moldova, Norway, Switzerland, Turkey, Ukraine
Russia	Asian and European parts
US & Canada	United States, Canada

Table S9. F-gas regulations currently implemented in the baseline scenario

Regulation/ agreement	Region scope	Gas	Emission source	Content that concerns F-gas emissions	Date entering into force
EU F-gas directive (EC 842/2006)	EU-wide	HFCs	Refrigeration and air-conditioning	Good practice options with leakage control of equipment in use and end-of-life recollection of scrapped equipment.	4 July 2007
			Aerosols	F-gas use prohibited in aerosol generators intended for entertainment and decorative purposes.	4 July 2009
			One component foams	F-gas use prohibited unless required to meet national safety standards	4 July 2008
		SF$_6$	Magnesium casting	SF$_6$ use prohibited	1 Jan 2008
			Windows	SF$_6$ use prohibited	4 July 2007
			Other SF$_6$ sources, e.g., tires, sports equipment, etc.	SF$_6$ use prohibited	4 July 2007
EU MAC Directive (EC 40/2006)	EU-wide	HFCs	Mobile air conditioners	Replacing the use of high GWP HFCs with cooling agents GWP$_{100}$ < 150 in all new vehicle models placed on the market.	1 Jan 2011
EU Directive on end-of-life vehicles (EC 53/2000)	EU-wide	HFCs	Scrapped mobile air conditioners	Recollection and proper handling of scrapped mobile air conditioners	18 Sep 2000
EU ETS Directive (EC/29/2009)	EU-wide	PFCs	Primary Al production	Industry needs to acquire tradable emission permits under the EU emission trading system	1 Jan 2012
EU Effort Sharing Decision (EC/406/2009)	EU-wide	All GHGs	All non-ETS sectors	Decision defines legally binding national GHG emission targets for non-ETS sectors. Target year is 2020, but countries need to comply with a linear emission path between 2013 and 2020.	2013
F-gas regulation (Regulation 517/2014)	EU-wide	HFCs, PFCs, SF$_6$	All F-gas	Limits the total amount of the most important F-gases that producers and importers are entitled to place on the market in the EU from 2015 onwards and phases them down in steps to one fifth of 2014 sales by 2030.	1 Jan 2015
National F-gas regulations	Austria	HFCs, PFCs, SF$_6$	All F-gas sectors	"HFKW-FKW-SF6-Verordnung" is more stringent than EU F-gas regulation in the control of emissions from foams.	2002
	Belgium	HFCs	Commercial and industrial refrigeration	End-of-life recovery initiated already 2005	2005
	Denmark	HFCs, PFCs, SF$_6$	All F-gas sectors	Deposit-refund scheme (1992), tax on F-gases on producers and importers (2001), ban on import, sale and use of new products containing F-gases with specific exemptions (2002).	1992
	Germany	HFCs, PFCs, SF$_6$	All F-gas sectors	In contrast to the EU F-gas regulation the "Chemikalien-Klimaschutzverordnung" specify maximum leakage rates and include the refrigerated transport sector.	2008
	Netherlands	HFCs	Air conditioners and refrigeration	Mandatory good practice with leakage control and end-of-life recovery.	1997

	Sweden	HFCs, PFCs, SF_6	All F-gas sectors	Environmental fees regulation also targeting F-gases (1998) and specific F-gas regulation (2007)	1998
Voluntary agreement	Global	PFCs	Semiconductor industry	All semiconductor producers should by 2010 reduce PFC emissions to a level 10 percent of 1995 emissions.	Starting in 2001
Voluntary Aluminum Industrial Partnership (VAIP)	United Sates	PFCs	Primary Aluminum production	To improve aluminum production efficiency while reducing perfluorocarbon (PFC) emissions	1995
Significant New Alternatives Policy (SNAP)	United Sates	HFCs, PFCs, SF_6	All F-gas sectors	Under Section 612 of the Clean Air Act (CAA), EPA's Significant New Alternatives Policy (SNAP) program reviews substitutes within a comparative risk framework.	1990
EPA's Air Conditioning Improvement Credits	United Sates	HFC	Mobile air-conditioning	Incentive to accelerate the use of low-GWP refrigerants	2015
Protection of Stratospheric Ozone: Change of Listing Status for Certain Substitutes under the Significant New Alternatives Policy Program	United Sates	HFCs	All sectors	Limit the use of high-GWP HFCs	2015
Act on the Rational Use and Proper Management of Fluorocarbons (Act no. 64 of 2001)	Japan	HFCs, PFCs, SF_6	All F-gas sectors	Necessary measures to reduce emission of HFCs, Comprehensive measures for reducing high GWP HFCs in newly revised law, Labelling and voluntary plan	2015
Swiss F-gas regulations	Switzerland	HFCs, PFCs, SF_6	All F-gas sectors	HFCs are banned in AC systems with a cooling capacity of more than 600 kW. Bans (with some exemptions) on HFC based solvents, foams, refrigerants, fire extinguishing agents, and spray cans containing HFCs.	2013
HFC levy	Australia	HFCs	Refrigeration, air-conditioning, foam, aerosol, etc.	A carbon equivalent price is imposed on import and manufacture of HFC refrigerants that are ozone safe but are powerful greenhouse gases.	2012
Clean Development Mechanism of the Kyoto Protocol	Developing countries	HFCs, PFCs, SF_6	All F-gas sectors	Control of HFC-23 emissions from HCFC-22 production through post-combustion, avoidance of HFC emissions in rigid Poly Urethane Foam (PUF) manufacturing, PFC reduction in primary Al production, SF_6 recovery and reclamation, etc.	1997
Montreal Protocol: Accelerated phase-out of ODS	Global	HCFCs	Refrigeration, air-conditioning, foam, etc.	Phase-out of HCFC's in Article 5 and non-Article 5 countries	2007

Table S10. Uncertainty in emissions for major F-gas sectors in GAINS

Sector	Emission factors	Emission factor used in the GAINS model*		Emissions in 2050 ($MtCO_{2eq.}$)	Uncertainty range
		Uncontrolled*	Controlled		
Aerosol	50-100%[a-f]	75%	75%	25.1	±33%
Stationary air-conditioning	1-13%[a,b,f]	10%	7%	1111.4	(-)54% to (+)2%
Commercial refrigeration	10-35%[a,b,f,g]	18-22%	12-15%	590.8	(-)38% to (+)59%
HCFC-22 production	1.5-4%[a,b,e,h]	3%	0.01%	389.1	(-)49% to (+)36%
Industrial refrigeration	7-25%[a-g]	11-13.7%	6.5-8%	163.7	(-)28% to (+)64%
Mobile air-conditioning	7-24%[e-j]	18-24%	9-12%	410.3	(-)18% to (+)82%
Refrigerated Transport	15-50%[a-h]	25-30%	20-24%	144.6	(-)37 to (+)66%

* Lower values for non-Article 5 and higher values for Article 5 countries.

Source: (IPCC, 2000[a]; USEPA, 2004[b]; IPCC, 2006[c]; UNFCCC, 2012[d]; IPCC/TEAP, 2005[e]; Tohka, 2005[f]; Gschrey et al., 2011[g]; Schwartz et al., 2011[h]; McCulloch and Lindley, 2007[i]; Koronaki et al., 2012[j])

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