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

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Abstract. This study uses the GAINS model framework to estimate current and future emissions of the fluorinated greenhouse gases HFCs/HCFCs, PFCs and SF_6 (F-gases), their abatement potentials and costs for twenty source sectors and 162 countries/regions, which are aggregated to produce global estimates. Global F-gas emissions are estimated at 0.95 Pg CO_2eq in 2005 with an expected increase to 3.7 Pg CO_2eq in 2050 if application of control technology remains at the current level. There are extensive opportunities to reduce emissions using existing technology and alternative substances with low global warming potential. Estimates show that it would be technically feasible to reduce cumulative F-gas emissions by 86 percent between 2018 and 2050. A reduction in cumulative emissions by 72 percent is estimated possible at a marginal abatement cost below 10 €/t CO_2eq. We also find that future F-gas abatement is expected to be relatively more costly for developing than for developed countries due to differences in the sector distribution of emissions and abatement potentials.

1 Introduction

Many fluorinated gases (F-gases) have very high global warming potentials (GWP), so small atmospheric concentrations can have large effects on global temperatures. In this work we identify and quantify all important sources of F-gas emissions at a global scale, the potential for reducing these emissions, and the associated abatement costs. Using the framework of the Greenhouse gas and Air pollution Interactions and Synergies (GAINS) model (http://magcat.iiasa.ac.at), we estimate global emissions of the F-gases HFCs, HCFCs, PFCs and SF_6 for 2005 and 2010 and with projections to 2050. Twenty source sectors (14 for HFCs/HCFCs, 2 for PFCs and 4 for SF_6 emissions) are identified and emissions are estimated separately for 162 country/regions. Although HCFCs as ozone-depleting substances (ODS) are subject to phase-out under the Montreal Protocol (MP) (UNEP, 2007) and therefore not addressed under the Kyoto Protocol (KP) (UNFCCC, 2014), they are equally strong greenhouse gases as HFCs and with HFCs as close substitutes. Hence, to account for the full global warming effect of the combined use of HFCs and HCFCs as coolants, we estimate the HCFC emissions in parallel with HFC emissions. To facilitate a comparison to other global emission inventories of F-gases only covering the Kyoto gases HFCs, PFCs and SF_6, we always display separate results for HCFCs. For each F-gas source sector, we identify a set of abatement options and estimate their reduction potentials and costs based on information available from publicly available sources. We also point out major sources of uncertainty and highlight critical gaps in knowledge.

Our work is an independently developed emission inventory with future projections of global F-gas emissions, which is detailed enough to allow for producing estimates of emissions and abatement costs at the sector and technology level for 162 country/regions of the World. This is an add-on to existing literature (Velders et al., 2009; Gschrey et al., 2011; Montzka et al., 2011; USEPA, 2013; Ragnauth et al., 2015; Velders et al., 2015) in that it provides information on both emissions and costs at the sector and technology level and therefore enables a high degree of resolution of the estimated emissions, abatement potentials and marginal abatement cost curves.

Our findings confirm previous findings (EDGAR, 2013; Gschrey et al., 2011; Velders et al., 2009) that in year 2005 emissions of HFCs, PFCs and SF_6 contributed about 0.7 Pg CO_2eq to global greenhouse gas emissions, while our baseline projection, reaching 3.7 Pg CO_2eq in 2050, is somewhat lower than the business-as-usual estimates of previous studies (Velders et al., 2015; Gschrey et al., 2011), as discussed further in Section 4.5.

Section 2 presents the methodology used to estimate emissions and abatement costs. Section 3 describes the development of emission scenarios. Section 4 presents results and comparison to previous studies. Section 5 discusses different sources of uncertainty and Section 6 concludes the study. More details on HCFC/HFC, PFC and SF_6 consumption, emission estimation, abatement potentials and costs are provided in Section S2 of the Supplement.

2 Methodology

2.1 F-gas emission estimation in GAINS

The estimation of current and future F-gas emissions and the potential for emission reductions and costs follow the standard GAINS model methodology (Amann et al., 2011) with some modifications specific to F-gases. To account for the wide spread in global warming potentials for different F-gases, emission factors are converted to carbon dioxide (CO_2) equivalents by multiplying the technology-specific emission factor with the respective GWP's over 100 years (IPCC, 2007b). Starting from April 2015, Annex-I (industrialized) countries report all greenhouse gases to the United Nations Framework Convention on Climate Change (UNFCCC) (2015) using GWPs from IPCC AR4 (IPCC, 2007a). As the official reporting to UNFCCC functions as basis for negotiations of future climate policy proposals, we apply IPCC/AR4 GWPs throughout this analysis, however, provide a comparison to IPCC/AR2 (IPCC, 1997) and IPCC/AR5 (IPCC, 2014) GWPs in the uncertainty analysis in Section 4. A complete list of GWPs for different substances recommended under the third, fourth and fifth IPCC ARs are presented in Table S2 of the Supplement.

For each pollutant (i.e., HFC, HCFC, PFC, and SF_6), the GAINS model estimates current and future emissions based on activity data, uncontrolled emission factors, the removal efficiency of emission control measures and the extent to which such measures are applied, as follows:

$$E_{i,p} = \sum_k \sum_m A_{i,k} ef_{i,k,m,p} GWP_{i,k,p} X_{i,k,m,p} \tag{1}$$

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where *i*, *k*, *m*, *p* represent the country, activity type, abatement technology, and pollutant, respectively, $E_{i,p}$ indicates emissions of specific pollutant *p* (i.e., here HFC, PFC, and SF_6) in country *i*, $A_{i,k}$ is the activity level of type *k* in country *i*, $ef_{i,k,m,p}$ is the emission factor of pollutant *p* for activity *k* in country *i* after application of control measure *m*, $GWP_{i,k,p}$ is the global warming potential of pollutant *p* when applied in country *i* to sector *k*, and $X_{i,k,m,p}$ is the share of total activity of type *k* in country *i* to which control measure *m* for pollutant *p* is applied.

Structural differences in emission sources are reflected through country-specific activity levels. Major differences in the emission characteristics of specific sources are represented through source-specific emission factors, which account for the extent to which emission control measures are applied. The GAINS model estimates future emissions by varying activity levels along exogenous projections of the development of human activity drivers and by adjusting implementation rates of emission control measures (e.g., Höglund-Isaksson et al., 2012). In a further step, uncontrolled emission factors and removal efficiencies for given control measures are summarized in adjusted emission factors. This approach allows for the capture of critical differences across economic sectors and countries that might justify differentiated emission reduction strategies on the basis of cost-effectiveness.

2.2 Activity data

Activity data used to estimate HFC emissions in the years 2005 and 2010 is derived from HFC consumption reported by Annex-I countries to the UNFCCC (UNFCCC, 2012). For non-Annex-I countries (i.e., primarily developing countries), HFC consumption data is extracted from available literature (MoEF, 2009; UNEP, 2011; GIZ, 2014; UNDP, 2014a-b). However, for many non-Annex-I countries very limited information is available on the HFC use, which prompts for the use of default assumptions adding to uncertainty in the estimates for these countries. For HFC use in refrigeration, air-conditioning, fire extinguishers, and ground-source heat pumps, HFC emissions are estimated separately for “banked” emissions, i.e., leakage from equipment in use, and for “scrapping” emissions, i.e., emissions released at the end-of-life of the equipment. This is also the format used by countries when reporting HFC emissions to the UNFCCC (2015). As domestic refrigerators are hermetic there is no risk of leakage during use and therefore only “scrapping” emissions are accounted for. At the end-of-life, the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery, recycling or destruction. In addition, for each HFC 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 UNEP (2007). Drivers for projections of HFC use differ by sector and are consistent with the macroeconomic and energy sector developments described by the Reference scenario of the IEA’s Energy Technology Perspectives 2012 (IEA/OECD, 2012) for non-EU countries and with the Reference scenario of the PRIMES model (Capros et al., 2013) for EU countries. Depending on the sector, different drivers have been used to drive future HFC emissions. E.g., the use of HFC-134a in mobile air conditioners is driven by a projection of the vehicle numbers taken from the GAINS model and consistent with the future development in vehicle fuel use by IEA/OECD (2012) and Capros et al., (2013). Driver for HFCs used in commercial and industrial refrigeration is the projection of value added for commercial and industry sectors, respectively. A complete list of HFC drivers with references is presented in Table S5 of the Supplement. Figure 1 shows the future development in major drivers for F-gas emissions on a global scale between 2005 (=100) and 2050 as they follow from IEA/OECD (2012) and Capros et al. (2013).

To the extent information is available from public sources, country-specific data have been collected for the most important industry source sectors, i.e., the production of difluorochloromethane (HCFC-22), primary aluminum and magnesium. Activity data for 2005 and 2010 production of primary aluminum and magnesium are taken from the U.S. Geological Survey (USGS, 2013a-b), except for the EU countries for which the source is the PRIMES model (Capros et al., 2013), and for China and India for which primary aluminum production data is obtained from the GAINS Asia project (Amann et al., 2008; Purohit et al., 2010). HFC-23 is generated as a by-product of HCFC-22 production for use as industry feedstock or emissive use (the later to be phased-out under the MP). Production levels are reported for historical years (UNEP, 2014) and with fractions of production for feedstock and emissive use, respectively, taken from IPCC/TEAP (2005). Projections of future production in these industries are assumed to follow growth in industry value added (IEA/OECD, 2012; Capros et al., 2013).

2.3 Emission factors

Sector-specific leakage rates are taken from various published sources (Harnisch and Schwarz, 2003; IPCC/TEAP, 2005; Tohka, 2005; Garg et al., 2006; Schwarz et al., 2011; UNFCCC, 2012; Höglund-Isaksson et al., 2012, 2013) and typically differ between industrialized (Annex-I) and developing (non-Annex-I) countries (Gschrey et al., 2011).

To convert emission factors to CO_2-equivalent terms, these have been multiplied with sector-specific GWPs. The GWPs of HFCs replacing ODSs ranges from 124 (HFC-152a) to 14,800 (HFC-23) (IPCC, 2007b) over 100 years and with different HFCs used to different extents in different sectors. To weigh the sector-specific GWPs by the shares of different types of HFCs commonly used in the respective sectors, we combine sector-level information provided by Gschrey et al. (2011) with country-specific information provided by Annex-I countries in the Common Reporting Format to the UNFCCC (UNFCCC, 2012). The sector-specific GWPs are presented in Table S2 of the Supplement.

Primary aluminum production, semiconductor manufacturing and flat panel display manufacturing are the largest known sources of tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6) emissions. PFCs are also relatively minor substitutes for ODSs. Over a 100-year period, CF_4 and C_2F_6 are, respectively, 7,390 and 12,200 times more effective than CO_2 at trapping heat in the atmosphere (IPCC, 2007b). The International Aluminium Institute (IAI) observed a median PFPB emission factor for eight Chinese smelters that is 2.6 times larger than the global PFPB technology average (IAI, 2009). Assuming the Chinese emissions factor is constant over time (Mühle et al., 2010), the revised PFC emissions factor for Chinese Al smelters of 0.7 tonne CO_2eq/tonne Al produced is used in this study, while the global PFPB technology average of 0.27 tonne CO_2eq/tonne Al produced is used for other countries/regions.

The GWP of SF_6 is 22,800, making it the most potent greenhouse gas evaluated by IPCC (IPCC, 2007b). It is used a) for insulation and current interruption in electric power transmission and distribution equipment, b) to protect molten magnesium from oxidation and potentially violent burning in the magnesium industry, c) to create circuitry patterns and to clean vapor deposition chambers during manufacture of semiconductors and flat panel displays, and d) for a variety of smaller uses, including uses as a tracer gas and as a filler for sound-insulated windows (USEPA, 2013). For the case of magnesium processing, SF_6 consumption factors of 1.65 kg SF_6/t Mg is used for China (Fang et al., 2013) and a default value (1.0 kg SF_6/t Mg) suggested by the IPCC (IPCC, 2006) is used for other regions.

2.4 Abatement costs

F-gas abatement costs per unit of activity in GAINS have been calculated as the sum of investment costs, non-energy operation and maintenance costs and energy-related costs (or savings). The unit cost of technology *m* in country/region *i* and year *t* is defined as:

$$C_{itm} = I_{im}\left[\frac{(1+r)^T \times r}{(1+r)^T - 1}\right] + M_{im} + \left(E_{im} \times p_{it}^{electr}\right) \tag{2}$$

Where $I_{im}\left[\frac{(1+r)^T \times r}{(1+r)^T - 1}\right]$ represents the annualized investment cost for technology *m* in country *i* and with interest rate *r* and technology lifetime of *T* years, M_{im} the non-energy related annual operation and maintenance cost for technology *m*, E_{im} the demand for electricity, and the electricity price in country *i* in year *t*.

The price of electricity is assumed linked to the gas price in the following way (Höglund-Isaksson et al., 2013):

$$p_{it}^{electr} = 3 + 2\, p_{it}^{gas} \tag{3}$$

The expected trajectory of future gas prices through 2030 follows IEA/OECD (2012) for non-EU countries and Capros et al. (2013) for EU countries.

The marginal cost per unit of reduced emissions is defined for each technology available to a sector as the unit cost divided by the difference between the technology emission factor and the no control emission factor, such that:

$$MC_{itm}^{Tech} = \frac{C_{itm}}{ef_{it}^{No\_control} - ef_{itm}} \tag{4}$$

where $ef_{it}^{No\_control}$ is the no control emission factor and ef_{itm} is the emission factor after abatement control has been implemented.

We refer to this as the "technology marginal cost". Within a sector, the technologies available are first sorted by their respective technology marginal cost. The technology with the lowest technology marginal cost is ranked the first-best technology and assumed adopted to its full extent in a given sector. The second-best technology is the technology with the second lowest technology marginal cost and is assumed available for adoption provided it can achieve an emission factor that is lower than the first-best technology. The marginal cost of the second-best technology when implemented in the marginal cost curve is defined as:

$$MC_{it2} = \frac{C_{it2} - C_{it1}}{ef_{it1} - ef_{it2}} \quad (5)$$

Hence, the marginal abatement cost curve displays the relationship between the cost of reducing one additional emission unit and the associated emission control potential.

Note that abatement costs are defined as the incremental cost of switching from the current technology to an enhanced technology in terms of greenhouse gas emissions. Many alternative technologies provide additional indirect emissions savings and monetary benefits through increased energy efficiency, as compared to traditional HFC technologies (Kauffeld, 2012). We have incorporated monetary benefits accrued to increased energy efficiency. Some alternative substances are known to be flammable and may need special precaution in handling and training of staff. For such substances to be considered feasible, we limit our options to substances that are known to already have wide application in the given sector. Transaction costs, e.g., the one-time cost of training staff in the use of a different substance and introduction of new safety routines, are not considered in the abatement cost. E.g., switching from high-GWP HFCs to ammonia (NH_3) in industrial refrigeration will initially require special attention paid to the handling as NH_3 has flammable properties. On the other hand, NH_3 is, and has for decades been, widely used in industrial refrigeration, which proves that its flammability is not an unsurmountable obstacle for adoption. Hence, the abatement cost for switching to NH_3 in industrial refrigeration is measured as the difference in costs between HFCs and NH_3 per cooling unit, where the latter is less expensive and also more energy efficient, thereby rendering a negative net cost for the option (see Table S6-S7 in the Supplement for more details on input parameters for costs).

2.4 Geographic coverage of F-gas in GAINS

Geographic coverage of F-gas emission estimates in the GAINS model is global, with the world divided into 162 regions. Emissions, abatement potentials and costs are calculated for each region, however for display purposes these are aggregated into 14 world regions, as shown in Table S8 of the Supplement.

3 Development of F-gas emission scenarios

3.1 Baseline scenario

To estimate F-gas emissions in the baseline scenario, we have assumed full implementation of legislation currently adopted to control F-gas emissions at the regional or national level based on publicly available information. Table 1 summarizes the F-gas legislation currently implemented and with effects considered in the baseline scenario. Further details on the intention, stringency and targets of the existing F-gas legislations are presented in Table S9 of the Supplement.

The first EU F-gas Regulation (EC 842/2006) was implemented in 2006 to control the release of F-gases from stationary cooling and refrigeration equipment as well as from aerosols, foams and a few other minor sources. The regulation further requires an increased use of alternative blowing agents for one-component foams, use of alternative propellants for aerosols, leakage control and end-of-life recollection and recycling of high- and mid- voltage switches, SF_6 replaced by SO_2 in magnesium production and casting, and a ban on the use of SF_6 in soundproof windows, sports equipment etc. The EU mobile (or motor vehicle) air conditioning (MAC) directive (2006/40/EC) bans the use of HFC-134a in mobile air conditioners from 2017. In 2014, a revised EU F-gas regulation (EC 517/2014) was adopted which places bans on the use of high-GWP HFCs primarily in refrigeration and air-conditioning sectors starting from January 2015 and also contains a phasedown of HFC consumption from a base level. By 2030, the new regulation is expected to cut EU's F-gas emissions by two-thirds compared to 2014 levels. Following the requirements of the amendment (EC/29/2009) of the EU-ETS Directive, PFC emissions from the primary aluminium (Al) industry are included in the EU-ETS emission cap. In addition to EU wide F-gas legislation, there is national legislation in place targeting F-gas emissions in Austria, Belgium, Denmark, Germany, Netherlands and Sweden. These regulations were typically put in place prior to the EU legislation, are more stringent, and address more specific sources than the EU regulation.

Apart from the EU, also Japan, USA, Australia, Norway and Switzerland have implemented national regulations to limit the use of high-GWP HFCs. These are all Non-Article 5 countries under the MP and have introduced HFCs several years ago as a mean to replace CFCs and HCFCs under the ODS phase out schedule. The approaches chosen comprise different regulatory measures including the use of market-based instruments such as taxes (Schwarz et al., 2011). In the United States, there are economic incentives in place to eliminate HFCs for use in mobile air-conditioners (USEPA, 2012) and recent regulations (USEPA, 2015) are expected to further limit the use of high-GWP HFCs. Similar new regulations are in place in Japan (METI, 2015). Switzerland banned HFCs in a series of air-conditioning and refrigeration applications from December 2013 (UNEP, 2014). In Australia, as part of the clean energy future plan, synthetic greenhouse gas (SGG) refrigerants attract an "equivalent carbon price" based on their global warming potential (GWP) since the 1st July 2012 (AIRAH, 2012).

HFC-23 emissions from HCFC-22 production are assumed fully controlled in OECD countries through post-combustion. The USEPA (2006) and UNEP (2007) project until 2050 a shift of most HCFC-22 production from OECD countries to China and other developing countries. Note that this refers to the production of HCFC-22 for feedstock use in industry, which is not required to be phased-out under the MP. Several studies (e.g. Wara, 2007; Miller et al., 2010; Miller and Kuijpers, 2011; Montzka et al., 2010) discuss the impact of Clean Development Mechanism (CDM)[1] projects on global HFC-23 emissions for this sector. In this analysis we assume that the impact of CDM on emissions from HCFC-22 production in developing countries remains at the current level in the future. In non-Annex-I countries, China has developed HFC phase-down programs, including capacity-building, collection and reporting of HFC emissions data, mobilization of financial resources for further actions to phase-down HFCs, research, development and deployment of environmentally sound, effective and safe alternatives and

[1] The Clean Development Mechanism (CDM) is one of the Flexible Mechanisms defined in the Kyoto Protocol that allows emission-reduction projects in non-Annex-I (developing) countries to earn certified emission reduction (CER) credits, each equivalent to one tonne of CO_2. These CERs can be traded and sold, and used by Annex-I (industrialized) countries to a meet a part of their emission reduction targets under the Kyoto Protocol.

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technologies, and multilateral agreements to phase down HFCs (UNFCCC, 2014). Belize, Burkina Faso, Colombia, Egypt and Paraguay require import licenses for HFCs (Brack, 2015). It is however unclear if these have had a negative effect on the use of HFCs and we therefore do not account for them in the baseline. Turkey is planning to strengthen legislation on ozone-depletion and fluorinated gases (UNEP, 2013) however, effects of planned policies are not included in the baseline. Paraguay and the Seychelles have implemented fiscal incentives including taxes and subsidies to encourage a switch from HFCs and HCFCs to alternative low GWP substitutes (Brack, 2015). These two countries are in GAINS modelled as part of larger regions (Other Latin America and Other Africa) and we are therefore not able to reflect the effect of these national legislations in the baseline.

The general trend in the aluminium industry is switching from existing HSS/VSS or prebake technologies to Point Fed Prebake (PFPB) technology. According to the 2013 Anode Effect Survey of the International Aluminium Institute (IAI), PFC emissions intensity (as CO_2eq per tonne of production) from the global aluminium industry has been reduced by more than 35 percent since 2006, almost 90 percent since 1990. With primary Al production having grown by over 150 percent over the same period, absolute emissions of PFCs by the Al industry have been reduced from approximate 100 Tg of CO_2eq in 1990 to 32 Tg of CO_2eq in 2013 (IAI, 2014). In EU-28, emissions from primary Al production are regulated under the EU-ETS system and control options with marginal costs falling below the expected ETS carbon price in the reference scenario (projected with PRIMES) are adopted in the baseline (Höglund-Isaksson et al., 2016). This means that with the natural turn-over of capital, all EU member states will have phased-in PFPB technology by 2020. Primary Al production in China is estimated at 55 percent of global production capacity of 58.3 Mt in 2015 (USGS, 2016) where almost all primary Al production facilities are employing the PFPB technology (Hao et al., 2016). For other non-EU-28 regions, primary Al smelters will use the baseline production technologies until 2050.

There is a voluntary agreement in place among semiconductor producers worldwide to reduce the release of PFC emissions to 10 percent below the 1995 emission level by 2010 (Huang, 2008). According to industry (WSC, 2016), over the 10-year period the semiconductor industry achieved a 32 percent reduction in PFC emissions, surpassing its voluntary commitment. Since 2010, the industry has set a new goal based on a normalized (i.e. relative to production levels) target instead of an absolute target and has established best practices for new manufacturing capacity that will continue to improve efficiency (WSC, 2016). Since PFC is only used by few companies in a country (Tohka, 2005) and as the amount of PFC use allows deriving production volumes, data on PFC use are often confidential. Therefore GAINS uses the volume of PFC emissions as activity variable for this sector. Further information is provided in Section S2.2 of the Supplement.

Finally, the baseline assumes full implementation of the accelerated HCFC phase-out schedule agreed to by the MP Parties in September 2007 (UNEP, 2007). The HCFC phase-out in Non-Article 5 (mainly developed) countries will have achieved a 90 percent reduction by 2015, but since climate co-benefits were not a condition or aspiration of the MP, transitions did not favor low-GWP alternatives, even where such had been developed and commercialized (EIA, 2012). Under the accelerated schedule, HCFC consumption in Article-5 (developing) countries will be frozen in 2013 at the average production levels of 2009 and 2010. More prominently, the Parties agreed to cut HCFC production and consumption in developing countries by 10 percent in 2015, 35 percent by 2020 and 67.5 percent by 2025, with the phase-out virtually completed in 2030. For each emission source, the fraction of HCFCs to HFCs in use is identified as per the latest information and modelled in GAINS following the accelerated phase-out schedule of HCFCs under the MP.

3.1 Maximum technically feasible reduction scenario

In the maximum technically feasible reduction (MFR) scenario, the abatement potential encompasses reductions in emissions through the application of technologies that are currently commercially available and already tested and implemented, at least to a limited extent. Table S6 of the Supplement presents abatement options for HFC emissions in GAINS and provide references to literature. HFC control options fall into four broad categories:

a) Good practice: This encompasses a package of measures including improved components, leak prevention during use and refill, maintenance and end of life recovery and recollection of refrigerants. The removal efficiency is 20 to 50 percent for the emissions banked in refrigeration and air-conditioning equipment and 80 to 88 percent for the emissions from scrapped equipment (Tohka, 2005; Höglund-Isaksson et al., 2013).
b) Switching to low-GWP HFCs: HFCs currently in use have relatively long atmospheric lifetimes—15 years on average—which makes GWPs relatively high, ranging from 1,430 to 14,800 times that of CO_2 over 100 years (IPCC, 2007b). Alternative HFCs offer shorter lifetimes and considerably lower GWPs, e.g., HFC-152a has a GWP of 124 and HFC-32 has a GWP of 675 (IPCC, 2007b). Moreover, use of HFC-32 in air-conditioning and heat pumps can improve energy efficiency by 5-10 percent depending on models (Daikin, 2016). For air-conditioning, removal efficiency when switching to HFC-32 is 68 percent for room air conditioners. Similarly, removal efficiency when switching to HFC-152a is more than 90 percent in foam, non-medical aerosol and other applications.
c) Switching to new cooling agents: In recent years, alternative substances with very short lifetimes of less than a few months have been developed and marketed, e.g., HFO-1234ze with a GWP of 6 for use in aerosols and foam products and HFO-1234yf with a GWP of 4 for mobile air-conditioners. The removal efficiency of new cooling agents exceeds 99% for mobile air-conditioning and aerosol/foam sectors.
d) Other non-HFC substances with low or zero GWPs: Commercial examples include hydrocarbons (e.g. R-290), NH_3, CO_2, dimethyl ether and a diversity of other substances used in foam products, refrigeration, air-conditioning and fire protection systems. Switching involves process modifications, e.g., changing the process type from ordinary to secondary loop systems (Halkos, 2010). Industrial ammonia systems are in general 15 percent more energy efficient than their HFC counterparts (Schwarz et al., 2011).

HFC-23 (GWP100 = 14,800) HFC-23 is an unwanted waste gas from the production of HCFC-22. HFC-23 can be abated by reducing the by-product rate through process optimization and by capturing the HFC-23 and installing a separate incinerator where it is thermally oxidized by burning a fuel together with air and steam. The HFC-23/HCFC-22 ratio is typically in the range between 1.5 and 4 percent (Schneider, 2011), depending on how the process is operated and the degree of process optimization that has been performed (McCulloch and Lindley, 2007). Process optimization reduces but does not eliminate

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HFC-23 emissions. To reduce the HFC-23/HCFC-22 ratio below 1 percent, thermal oxidation in a separate incinerator is required (IPCC/TEAP, 2005). For this reason several CDM projects abate HFC-23 by installing a new incinerator where it is thermally oxidized. The removal efficiency of incineration of HFC-23 is taken to be virtually complete (99.99 percent) (World Bank, 2010).

In GAINS, four current production technologies for primary aluminium are considered: Side worked prebake (SWPB), Centre worked prebake (CWPB), Vertical stud Söderberg (VSS), and Point feeder prebake (PFPB). The identified PFC control options include retrofitting plants with existing technologies or converting the plants to PFPB technology. Inert anode technology with 100 percent removal efficiency is in GAINS assumed available as an abatement option from 2035 onwards (IEA/OECD, 2010). Table S7 of the Supplement lists the abatement measures for PFC emissions in the primary aluminium production and semiconductor manufacture sectors and provide references to literature. The removal efficiency of conversion of existing primary Al production technologies (VSS, SWPB and CWPB) to PFPB technology is more than 85 percent whereas retrofitting has a removal efficiency of approximately 26 percent (Harnisch et al., 1998; Harnisch and Hendriks, 2000).

The GAINS model considers three control options for reducing SF_6 emissions: a) good practice, which for high and mid-voltage electrical switchgears (HMVES) includes leakage reduction and recycling of recollected SF_6 from end of life switchgears, b) use of SO_2 as an alternative to SF_6 in magnesium production and casting, and c) phase-out of SF_6 for several applications (i.e. soundproof windows). A list of SF_6 control options considered in GAINS is also presented in Table S7 of the Supplement together with references to literature. The removal efficiency of good practices in HMVES is 84 percent (Tohka, 2005) whereas use of SO_2 as an alternative to SF_6 in magnesium production and casting is taken to have a removal efficiency of 100 percent.

In the near-term, abatement opportunities within refrigeration and air-conditioning are partially restricted because many of the abatement options identified apply only to newly manufactured equipment and are thus limited by the turnover rate of the existing refrigeration and air-conditioning stock. Unless already regulated in the baseline and therefore already adopted to a large extent, the general assumption in the MFR scenario is that developed countries (i.e., Non-Article 5 countries under the MP) can replace at least 75 percent of its use of HFCs in refrigeration and air-conditioning equipment by 2025 and 100 percent from 2030 onwards. For developing countries (i.e., Article 5 countries under the MP) the corresponding assumptions are 25 percent in 2020, 50 percent in 2025, 75 percent in 2030, and 100 percent from 2035 onwards. For the use of HFCs in aerosols, a general additional limit on applicability of alternative substances is set to 60 percent (UNFCCC, 2012), reflecting the difficulties with replacing HFC-134a and HFC-227ea in medical dose inhalers for all patient groups as no other compounds are proven to meet the stringent medical criteria required (IPCC/TEAP, 2005; UNEPA, 2016).

3.1 Politically feasible reduction scenarios

The baseline and the MFR scenarios define the upper and lower technical boundaries for the development in future F-gas emissions, with MFR defining the lowest technically feasible emission level achievable without regarding cost limitations due to financial constraints. Depending on the availability of funds and the relative importance given by policy-makers to the mitigation of climate change in comparison to other policy-relevant needs, the politically feasible emission scenario is defined by the lowest emission level attainable given a politically acceptable marginal abatement cost level. The latter is usually expressed in terms of a politically acceptable carbon price level. Within the technical boundaries defined by the baseline and MFR scenarios, we therefore develop alternative scenarios defining the expected development in future F-gas emissions when the marginal abatement cost does not exceed zero, five, ten, 15, 20, 40, 60 ,80, 100 and 200 €/tCO_2eq, respectively.

4 Results

4.1 Baseline F-gas emissions 2005 to 2050

Baseline F-gas emissions for the period 2005 to 2050 are presented in Figure 2. For historical years 2005 and 2010, the contribution from F-gas emissions to global warming are estimated at 0.95 and 1.14 Pg CO_2eq, respectively, whereof the release of HCFCs accounted for about a quarter. The release of other F-gases (HFCs, PFCs and SF_6) are estimated at 0.70 and 0.85 Pg CO_2eq, respectively in 2005 and 2010. In 2010, 32 percent of these emissions are released as HFCs from stationary air conditioning and refrigeration, 15 percent as HFC-134a from mobile air conditioners, 19 percent as HFC-23 emissions from HCFC-22 production for emissive and feedstock use, 8 percent as HFCs from use in aerosols, foams, solvents, fire-extinguishers, ground-source heat pumps, 14 percent as SF_6 from high- and mid- voltage switches, magnesium production, soundproof windows and other minor sources, and 13 percent as PFCs from primary aluminium production and semiconductor industry.

Baseline HFC, PFC and SF_6 emissions are estimated to increase by a factor of five between 2005 and 2050, as shown in Figure 2. The growth is mainly driven by a six fold increase in demand for refrigeration and air conditioning services, which in turn is driven by expected increase in per capita wealth in developing countries combined with the effect of replacing CFCs and HCFCs with HFCs in accordance with the revised MP. Under the MP, HCFCs in emissive use should be virtually phased out by 2030, but still allowing for refills of the existing stock until 2040. HFC-23 emissions from HCFC22 production for feedstock use in industry is expected to grow significantly in China following expected growth in industry value added. The current application of post-production incineration technology is applied to 36 percent of production in China and assumed in the baseline to remain at this level in the future (Feng et al., 2012).

Between 2005 and 2050, PFC emissions are expected to grow by 25 percent, which is a combination of expected growth in industry value added and emission contractions following expected switches from outdated HSS/VSS or prebake technologies to more efficient Point Fed Prebake (PFPB) technology in primary aluminium production. SF_6 emissions are expected to increase by almost 50 percent over the same period due to expected growth in emissions from high- and mid- voltage switches as electricity consumption increases and due to expected growth in magnesium production, which is dominated by China (USGS, 2013b) and without adoption of control expected in the baseline.

4.2 The future technical abatement potential

Figure 3 shows that there are extensive opportunities to reduce F-gas emissions through existing technologies or by replacement with low-GWP alternative substances. In the near-term, abatement opportunities within refrigeration and air-conditioning are limited by the turnover rate of the existing refrigeration and air-conditioning stock (see Section 3.2). The full technical abatement potential is therefore expected attainable from 2035 onwards and then estimated at 97 percent below baseline emissions, which reflects the deep cuts in emissions found technically feasible across all source sectors as shown in Figure 3.

4.3 The cost of future technical abatement potentials

Figure 4 shows the estimated marginal abatement cost curves for global F-gas emissions in 2020, 2030, 2040 and 2050 for moving between the baseline and the MFR emission scenarios. The mitigation potential is extended over time primarily due to the expected increase in baseline emissions and to a lesser extent by short-run technical limitations to fully phase-in the available abatement options. Net savings on abatement costs are primarily expected from replacement of the use of HFCs with NH_3 in industrial refrigeration, switching from high to low HFCs (e.g., HFC-125a) in foam blowing, switching from the use of HFCs to hydrocarbons (e.g., propane or butane) in residential air-conditioning, and switching from HFCs to CO_2-based systems in transport refrigeration. The lower part of Figure 5 shows that global annual cost-savings from these options are estimated at over 15 billion Euro in 2050. The upper part of Figure 5 shows the estimated total annual cost of implementing costly F-gas abatement options below a marginal cost of 200 €/t CO_2eq (which corresponds to 98 percent of the MFR abatement potential). The highest cost is attributed to the replacement of HFC-134a in cars with HFO-1234yf. The annual cost of implementing this option globally is estimated at almost 35 billion Euro in 2050. Replacing the HFC-134a use in other types of vehicles is estimated to add 8 billion Euro annually in 2050. The total annual cost of implementing all other costly options are estimated at 14 billion Euro in 2050. Hence, global implementation of all options in 2050 (thereby achieving 98 percent of MFR), is estimated at a net annual cost of 41 billion Euro, whereof costly options make up 57 billion and cost-saving options 16 billion Euro per year.

Figure 6 shows the estimated development in future F-gas emissions in the baseline and MFR scenarios at different carbon price levels (i.e. maximum marginal abatement cost levels). According to these estimates, a moderate carbon price level of 10 €/t CO_2eq would provide enough incentives to achieve significant emission reductions of 80 percent below baseline in 2035. However, without allowing for a further increase in the carbon price in the long run, a continued increase in demand for F-gas services is expected to result in a 36 percent increase in global F-gas emissions between 2035 and 2050.

4.4 Cumulative F-gas emissions and costs 2018-2050

To display the effect on emissions from different climate policy ambition levels, we sum up the expected cumulative emissions released over the period 2018 to 2050 for alternative carbon price levels. By setting a positive carbon price, all abatement options that come at a marginal abatement cost lower than the carbon price can be expected to be implemented as they will render a saving to the user compared with paying the carbon price. We measure the cumulative emissions starting from year 2018 as this is considered the earliest year from which new climate policy can realistically be in place. Figure 7 shows the estimated cumulative emissions 2018 to 2050 at different carbon price levels and for Article 5 (developing) countries and non-Article 5 (developed) countries separately. As shown, in the baseline Article 5 countries can be expected to release 62 Pg CO_2eq of F-gases, while the contribution from non-Article 5 countries is expected to release 19 Pg CO_2eq over the entire period. With climate policies implemented globally and corresponding in stringency to a carbon price of 10 €/tCO_2eq, the cumulative release over the entire period is estimated at 17 Pg CO_2eq from Article 5 countries and 6 Pg CO_2eq from non-Article 5 countries. Hence, globally this means a reduction in cumulative F-gas emissions from 81 to 23 Pg CO_2eq over the period 2018 to 2050, i.e., a reduction in global emissions by 72 percent.

Figure 8 shows estimated total cost of achieving the respective cumulative emission reductions shown in Figure 7. As shown, non-Article 5 (developed) countries have considerable opportunities to reduce emissions through options that render cost-savings. These include a switch from current use of HFCs to less expensive alternative low-GWP substances in industrial refrigeration, foam blowing, residential air-conditioning and refrigerated transport, and relatively limited release of F-gases from industrial processes. The cumulative net cost of abatement over the period 2018 to 2050 therefore only turns positive at a carbon price exceeding 100 €/t CO_2eq. For developing countries, with relatively large emissions from industrial processes, the net cumulative abatement cost turns positive already at a carbon price of 40 €/t CO_2eq.

4.5 Comparison to other studies

Figure 9 shows a comparison between our baseline estimate of global F-gas emissions 2005 to 2050 and business-as-usual scenarios of other studies. Our findings confirm previous findings (EDGAR, 2013; Gschrey et al., 2011; Velders et al., 2009) that in year 2005 emissions of HFCs, PFCs and SF_6 contributed about 0.7 Pg CO_2eq to global greenhouse gas emissions. IPCC/TEAP (2005) projected F-gas emissions at a sectoral level until 2015. The projections are based on sectoral data on banked and emitted emissions in 2005 as well as projections by SROC (IPCC/TEAP, 2005) and updated projections of HFC banks and emissions for the period 2005–2020 by TEAP (UNEP, 2009). The projection to 2015 is very close to the baseline emissions estimated in GAINS.

Our baseline projection, reaching 3.7 Pg CO_2eq in 2050, is somewhat lower than the business-as-usual estimates of 4 to 5.4 Pg CO_2eq in 2050 by Velders et al. (2015) and Gschrey et al. (2011). The reason for the difference in projected emissions can be sought in the use of different drivers. Velders et al., (2015) use GDP and population growth rates from the IPCC SSP scenarios (O'Neill et al., 2012; IIASA, 2012) as drivers for F-gas emissions, while we use more sector-specific drivers (e.g., growth in commercial or industry value added) taken from the macroeconomic projections by Capros et al., (2013) for Europe and IEA/OECD (2012) for the rest of the World. Another reason may be differences in the sector-specific GWPs used. Just like Velders et al. (2015), we take account of the effects of the most recently implemented F-gas regulations, e.g., the 2014 revision of the F-gas regulation of the European Union, and therefore differences in the level of regulation should not contribute to differences in future emissions. The most recent business-as-usual scenario from Velders et al. (2015) and the GAINS baseline presented here project almost twice the global F-gas emissions in 2050 than the SRES B1 family of scenarios (1.9 Pg CO_2eq), that emphasises global solutions to economic, social, and environmental sustainability (IPCC/SRES, 2000). In 2050, GAINS estimates are 14 percent higher than the SRES A1 family of scenarios (3.2 Pg CO_2eq) that describes a future world of very rapid economic growth. Our estimates are approximately 40 percent higher than the SRES A2 and SRES B2 family of scenario, which project 2.1 and 2.2 Pg CO_2eq F-gas emissions in 2050. The higher projections of the more recent studies, including this one, can be explained by a strong increase in the use of F-gases with high GWPs in recent years, which are reflected in the sector-specific GWPs derived from the shares of commonly used HFCs reported by Annex-I countries to the UNFCCC (2015).

USEPA (2013) provides global projections of F-gases at regional and sectoral level until 2030. Their estimate for historical years is close to GAINS, but display a stronger increase in emissions between 2020 and 2030. In 2030, USEPA project global F-gas emissions at 2.6 Pg CO_2eq, which is 28 percent higher than the GAINS estimate for the same year.

Just like (Fisher et al., 2007), we find that there are significant opportunities to reduce F-gas emissions through adoption of existing alternative substances and technology.

5 Uncertainty analysis

It is important to acknowledge that there are several potential sources for uncertainty in the estimated emissions, abatement potentials and associated costs. This section focuses on uncertainty in the chosen methodology and information input used in the derivation of emission factors and costs. It does not address uncertainty in the projections of activity drivers as these have been taken from external sources (IEA/OECD, 2012; Capros et al., 2013). Uncertainty ranges presented in Table S10 are derived from default ranges suggested in the IPCC guidelines for National Greenhouse Gas Inventories (IPCC, 2006) and other published literature (IPCC, 2000; USEPA, 2004; UNFCCC, 2012; IPCC/TEAP, 2005; Tohka, 2005; Garg et al., 2006; Gschrey et al., 2011; Schwartz et al., 2011; McCulloch and Lindley, 2007; Koronaki et al., 2012). As mentioned in the previous section, HFCs are in the baseline expected to contribute to nearly 90 percent of global F-gas emissions in 2050. Figure 10 presents ranges of uncertainty for major HFC sectors contributing 84 percent of global HFC emissions in 2050. Other HFC sectors (i. e. fire extinguishers, foam, solvents etc.) are not incorporated due to lack of relevant data. Moreover, we do not attempt to sum sectoral uncertainty ranges at the global scale, as it is difficult to estimate relative uncertainty between sectors. Based on this data, global baseline emission estimates are most affected by uncertainty in estimates in stationary air conditioning followed by commercial refrigeration and mobile air conditioning. To reduce uncertainty in emission estimates, it would be of particular interest to obtain measurement data on sectoral emission rates of refrigerants in various world regions to complement currently available information from Europe and North America (Schwarz and Harnisch, 2003; Schwarz, 2005; MPCA, 2012; UNFCCC, 2012). Equally important would be to improve access to measurement data which can verify reported figures, e.g. HFC-23 emissions in HCFC-22 production for major HCFC-22 producing countries.

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Also note that GWP values are being continually revised to reflect current understanding of the warming potentials of CO_2 and other greenhouse gases. Figure 11 presents the impact on global F-gas emissions when using different GWPs taken from the second, fourth and fifth assessment reports of IPCC (see: Table S2). In 2050, global F-gas emissions in the baseline are estimated at 3.2 Pg CO_2eq using GWPs from the Revised 1996 IPCC guidelines (IPCC, 1997), whereas recent GWP values (IPCC, 2013) indicate 18 percent higher emissions in 2050 when converted to CO_2eq units.

Uncertainty in estimates is also affected by the quickly evolving development of alternative refrigerants and technologies in these sectors, with efficiencies in emission removal increasing and costs decreasing as research and market shares expand (USEPA, 2013). Thus, the use of current costs and removal efficiencies of existing control options is likely to render conservative estimates about the future abatement potentials and costs.

Uncertainty about the opportunities to exploit economies of scale when implementing different systems in different sectors adds to uncertainty in unit costs. E.g., recovery from large equipment is more cost-effective than for small equipment, as the amount of refrigerant recoverable is greater and the relative amount of technician time needed to perform the recovery is smaller. Other sources of uncertainty affecting costs include uncertainty in estimates of the amount of refrigerant recoverable from equipment at service and disposal as it will differ by the type of equipment. Similarly, because leak repair can be performed on many different equipment types and can involve many different activities/tools, it is difficult to determine an average cost of such repairs or the average emission reduction associated with them. This analysis, relies on broad assumptions about costs available in published literature (Tohka, 2005; Schwarz et al., 2011; Höglund-Isaksson et al., 2013; USEPA, 2013) and is not able to reflect specific local conditions affecting costs and removal efficiencies of different technologies.

6 Conclusions

Flourinated gases (F-gases) are potent greenhouse gases that contribute to global warming if released to the atmosphere. This analysis identifies and quantifies major global sources of F-gas emissions as well as technical opportunities and costs for abatement. It also pinpoints important sources of uncertainty in emission estimations, which could serve to improve future estimates. Results from the GAINS model suggest that in a baseline scenario that only takes into account effects on emissions from already adopted legislation and voluntary agreements, global emissions of the F-gases HFC, PFC and SF_6 are expected to grow by a factor of five between 2005 and 2050 (from 0.7 Pg CO_2eq. in 2005 to 3.7 Pg CO_2eq. in 2050). In particular, a sharp increase in emissions from air-conditioning and refrigeration sectors in developing countries contributes to increased emissions. We find that existing abatement technologies could reduce emissions by up to 97 percent below annual baseline emissions in the long run. Due to inertia in the replacement of current technology in the short run, it is considered technically feasible to reduce cumulative F-gas emissions released over the entire period 2018 to 2050 by 86 percent.

Abatement costs are found relatively low and at a carbon price of 10 €/t CO_2eq incentives to adopt F-gas abatement are expected strong enough to remove 72 percent of cumulative baseline F-gas emissions over the period 2018 to 2050. We find that future F-gas abatement is expected to be relatively more costly for developing than for developed countries due to differences in the sector distribution of emissions. Due to large opportunities in developed countries to switch from current use of HFCs to less expensive alternative low-GWP substances in industrial refrigeration, foam blowing, residential air-conditioning and refrigerated transport, and relatively limited release of F-gases from industrial processes, the cumulative net cost of abatement over the period 2018 to 2050 does only turn positive at a carbon price exceeding 100 €/t CO_2eq. For developing countries, with relatively large emissions from industrial processes, the net cumulative abatement cost turns positive already at a carbon price of 40 €/t CO_2eq. Hence, a fair and cost-effective distribution of the burden to control future global F-gases across all sectors and regions, calls for a policy mechanism that can redistribute costs from developed to developing countries.

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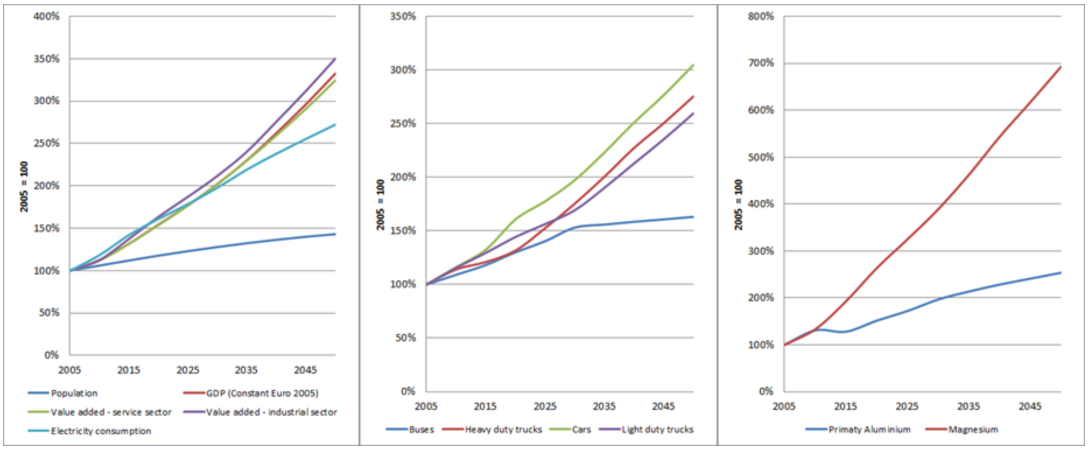

Figure 1: Global development 2005–2050 in major drivers for F-gas emissions entering model estimations from external sources

Source: (IEA/OECD, 2012; Capros et al. 2013; USGS, 2013a-c)

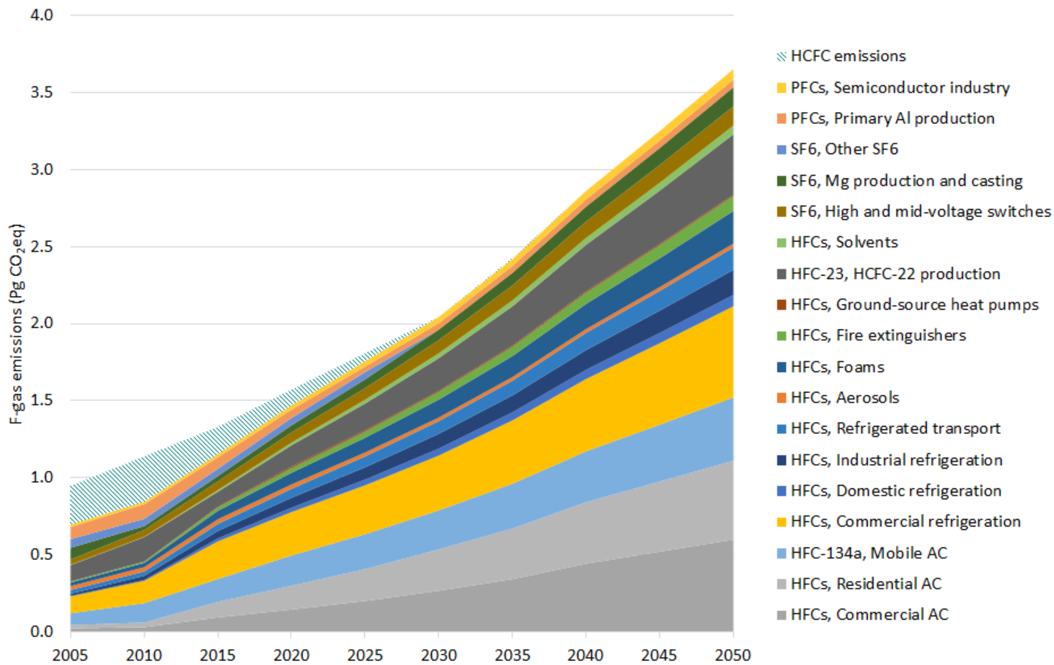

Figure 2: Baseline emissions of F-gases (HCFCs, HFCs, SF_6 and PFC) 2005 to 2050 by source sector. To facilitate comparison to other studies only reporting HFCs, SF_6 and PFCs, the HCFC emissions are summed up at top of the graph.

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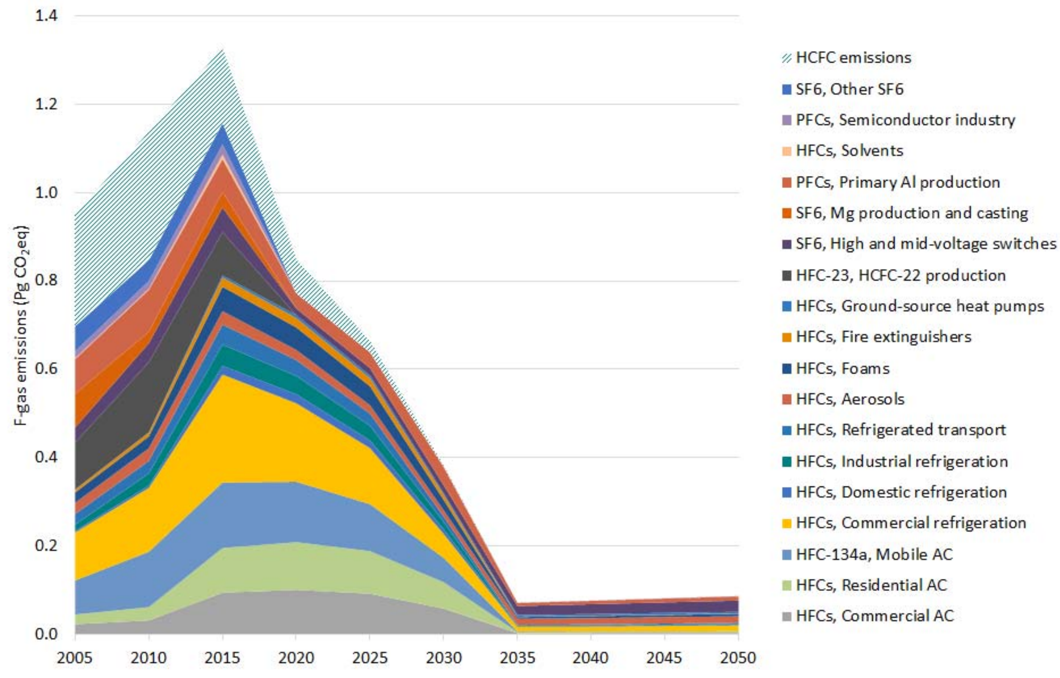

Figure 3: F-gas emissions in MFR scenario, i.e., after maximum technically feasible reduction 2020 to 2050.

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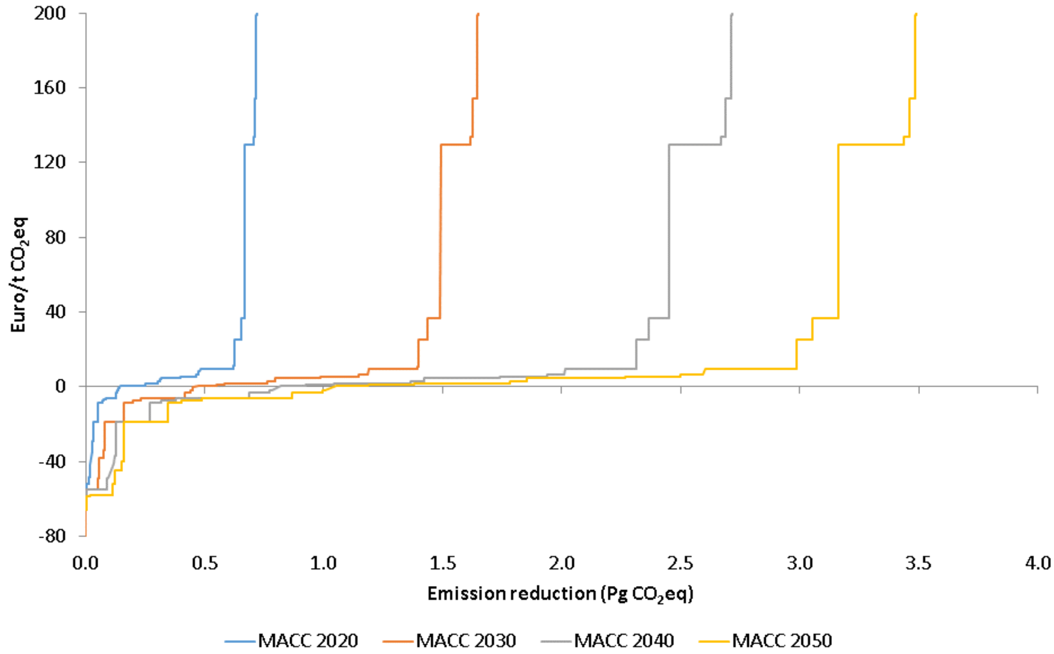

Figure 4: Marginal abatement cost curves in 2020, 2030, 2040 and 2050 for reducing global emissions of F-gases.

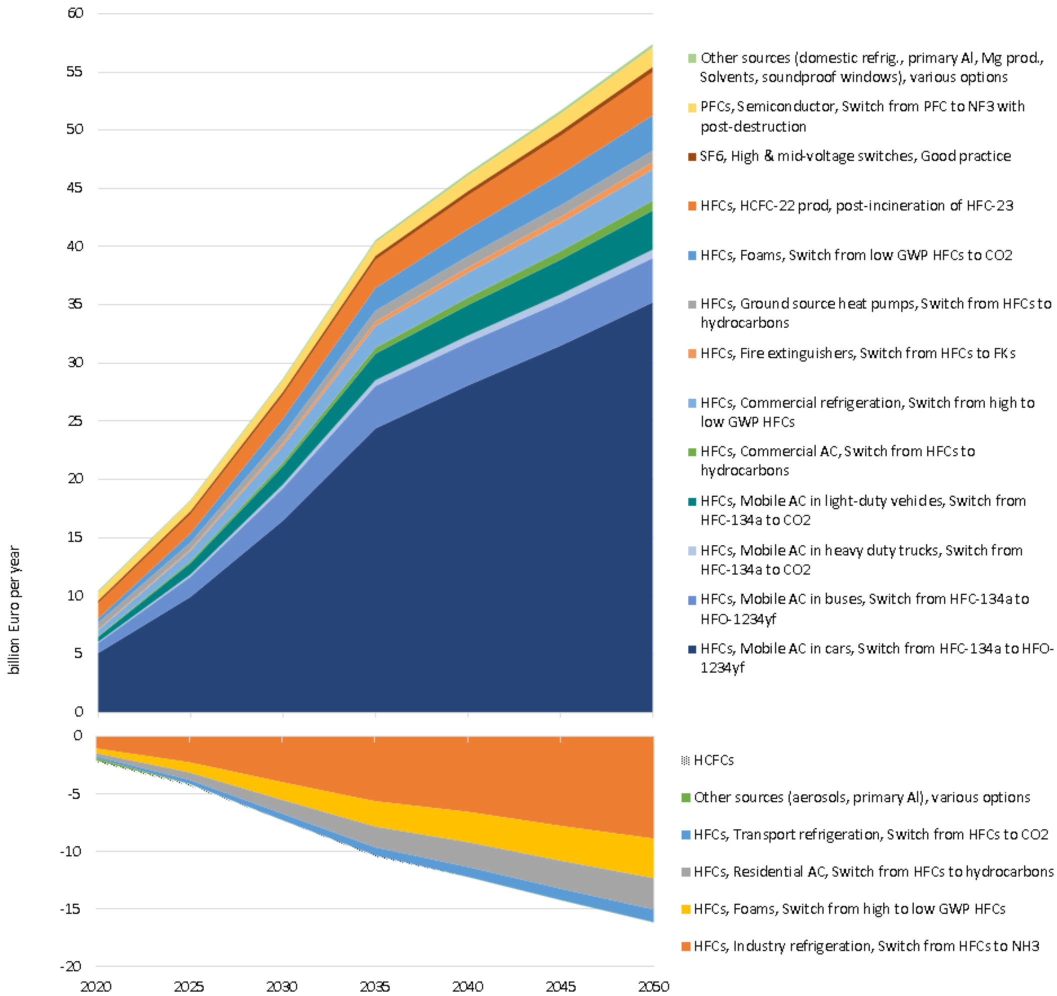

Figure 5: Total annual costs by control option for implementation of abatement options found available at a marginal cost below 200€/tCO_2eq (corresponding to 98 percent of MFR abatement potential).

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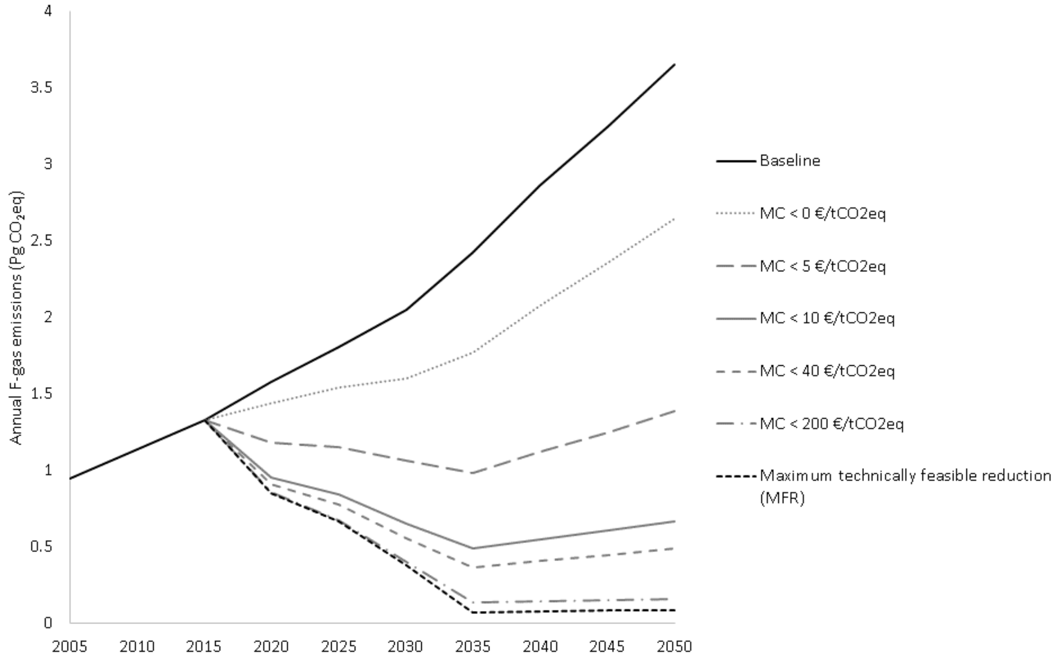

Figure 6: Estimated emission pathways for F-gas emissions (HFCs/HCFCs, PFCs, SF_6) at different carbon price levels.

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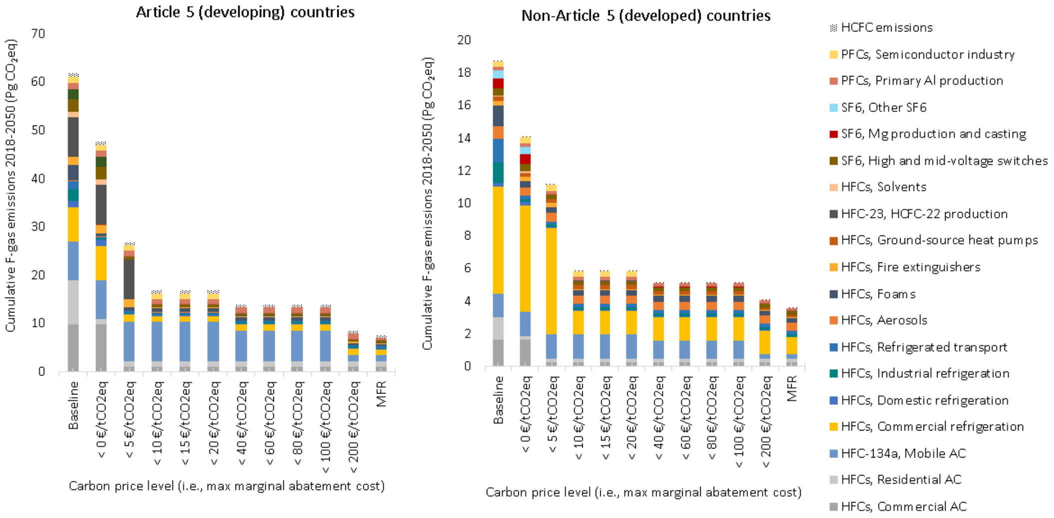

Figure 7: Estimated cumulative F-gas emissions released over the period 2018-2050 at different carbon price levels in Article 5 (developing) countries and Non-Article 5 (developed) countries.

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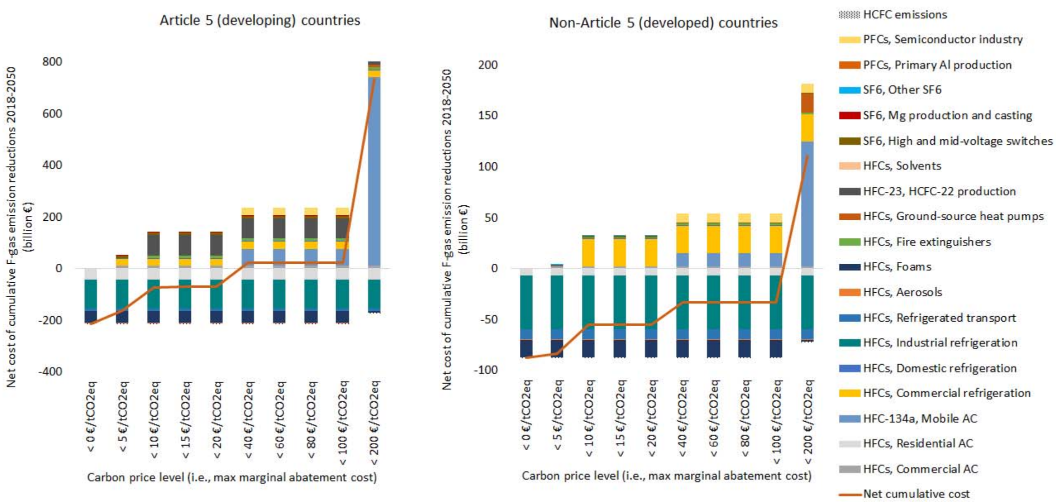

Figure 8: Net costs of cumulative reductions in F-gas emissions over the period 2018-2050 at different carbon price levels in Article 5 (developing) countries and Non-Article 5 (developed) countries.

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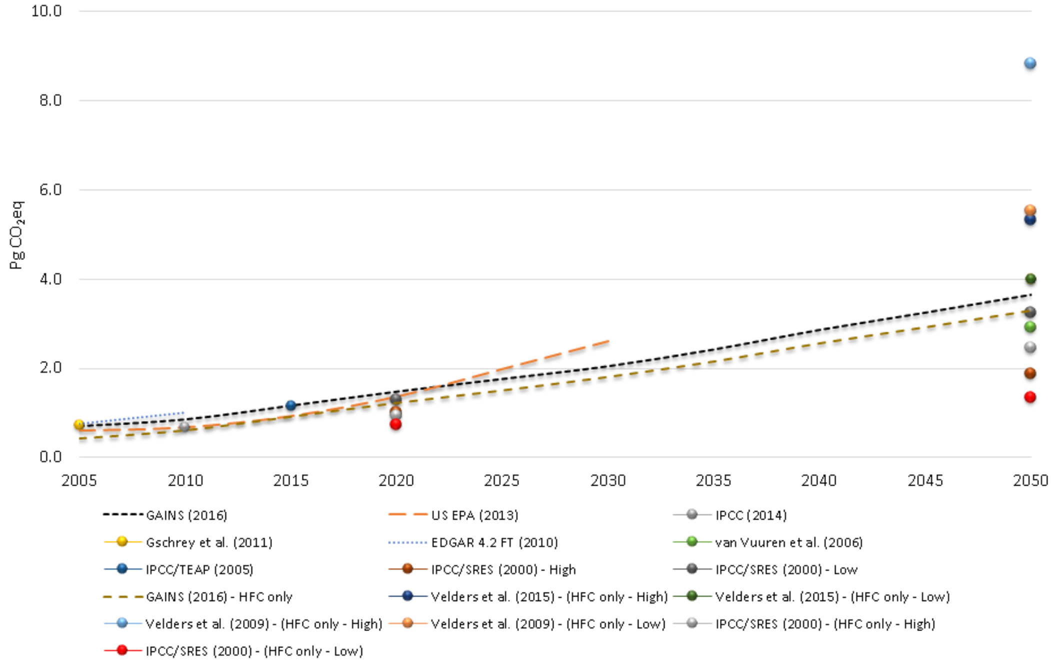

Figure 9: Comparison of GAINS emissions with other F-gas business-as-usual scenarios

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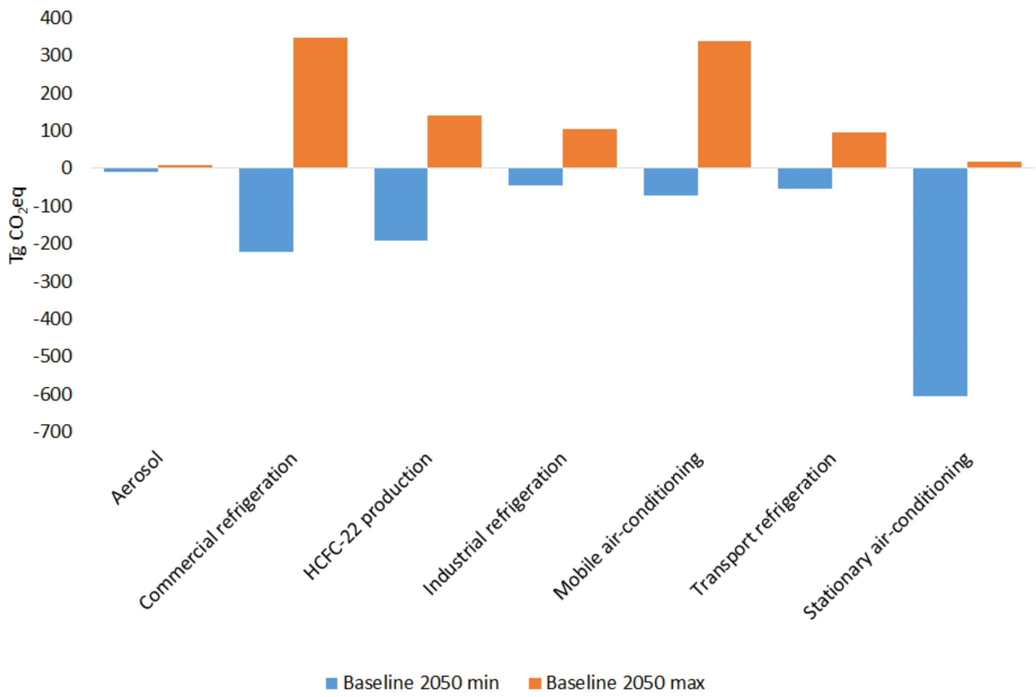

Figure 10: Uncertainty ranges by sector for global F-gas emission estimates.

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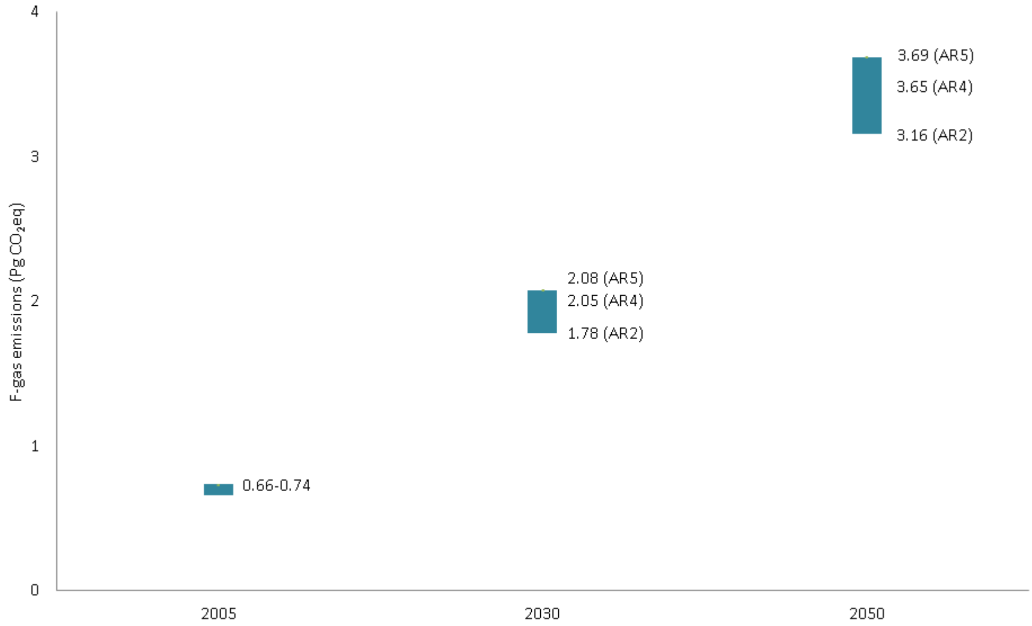

Figure 11: Global F-gas emissions using different GWP's.

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Table 1: Currently implemented F-gas regulations with effects accounted for in the baseline scenario.

Region scope	Regulation/ agreement	Year entering into force	Targeted emission source(s)
European Union wide	EU F-gas directive (EC 842/2006)	2007	HFCs in commercial and residential air conditioning, commercial and industrial refrigeration, domestic hermetic refrigerators, refrigerated transport, aerosols, one-component foams. SF_6 in Mg casting, soundproof windows, other SF_6 sources, e.g., tyres, sport equipment etc.
	EU MAC Directive (EC 40/2006)	2011	HFC-134a in mobile air conditioners
	EU Directive on end-of-life vehicles (EC 53/2000)	2000	HFC-134a in scrapped mobile air conditioners
	EU ETS Directive (EC/29/2009)	2012	PFCs in primary aluminium production
	EU Effort Sharing Decision (EC/406/2009)	2013	All GHG source sectors not covered under the EU Emission Trading System (ETS), which includes all F-gas sources except primary Al production
	F-gas regulation (Regulation 517/2014)	2015	All HFCs, PFCs and SF_6 sources
National F-gas regulations within the EU	Austria	2002	All HFCs, PFCs and SF_6 sources
	Belgium	2005	HFCs in commercial and industrial refrigeration
	Denmark	1992	All HFCs, PFCs and SF_6 sources
	Germany	2008	All HFCs, PFCs and SF_6 sources
	Netherlands	1997	HFCs in air conditioners and refrigeration
	Sweden	1998	All HFCs, PFCs and SF_6 sources
Worldwide	Voluntary agreement of Semiconductor industry	2001	PFCs in semiconductor industry
United States	Voluntary Aluminum Industrial Partnership (VAIP)	1995	PFCs in primary aluminum production
	Significant New Alternatives Policy (SNAP)	1990	All HFCs, PFCs and SF_6 sources
	EPA's Air Conditioning Improvement Credits	2015	HFCs in mobile air-conditioning
	Protection of Stratospheric Ozone: Change of Listing Status for Certain Substitutes under the Significant New Alternatives Policy Program	2015	All HFCs, PFCs and SF_6 sources
Japan	Act on the Rational Use and Proper Management of Fluorocarbons (Act no. 64 of 2001)	2015	All HFCs, PFCs and SF_6 sources
Switzerland	Swiss F-gas regulations	2013	All HFCs, PFCs and SF_6 sources
Developing countries	Clean Development Mechanism (CDM) under the Kyoto protocol	1997	All HFCs, PFCs and SF_6 sources
Article 5* and Non-article 5** countries	Montreal Protocol: accelerated phase-out of HCFCs	2007	

*preferably developing countries; **preferably developed countries