Referee #1 (Anonymous)

I am in favor of publishing the paper after following points have been carefully considered.

Authors’ Response: We thank the Anonymous Referee for his/her constructive comments and many helpful suggestions on how to improve the manuscript. Below we provide detailed point by point replies to the questions. Referee comments are quoted in italics and authors’ responses in blue.

1. *The term “F-gas” is somehow reserved for the HFCs, PFCs, SF6 regulated for example in the F-gas directive. The definition of this term as it is done in the paper (i.e. by including HCFCs) is therefore problematic. Authors should come up with a new term or just use this F-gases just as it is generally used and combine it with the HCFCs. E.g. “emissions of F-gases and HCFCs: : :”. Anyway, HCFCs are not really at the core of this analysis. For me it was for example not clear where authors got there information about activities and emission factors for HCFCs. Is that related to UNEP reporting or just a ratio with F-gases? Maybe it would be better to not really calculate emissions for HCFCs anymore but just focus on the HFCs.*

   Authors’ Response: Yes, we agree with the reviewer that the term “F-gases” should be reserved for HFCs, PFCs and SF_6. In the revised version we make sure to use the term only for these three substance groups. Although phase-out of HCFCs is already addressed under the Montreal Protocol (MP) and therefore not a target of interest when analyzing future abatement efforts in F-gases, we still find it useful to keep track of and display baseline HCFC emissions in parallel to HFCs, since HCFCs are very close HFC substitutes with equally strong global warming potentials. We will, however, make it clearer to the reader that the HCFC reporting is only for the purpose of “keeping track” and not intended as a potential target for future abatement opportunities.

   We have estimated the total refrigerant (HCFC/HFC) consumption at the sectoral level. For Annex-I countries (primarily non-Article 5 parties) HFC consumption in years 2005 and 2010 are taken as reported to the UNFCCC (UNFCCC, 2012). For non-Annex-I countries (i.e., primarily Article 5 parties), information on HCFC/HFC consumption by sector in years 2005 and 2010 is taken from available literature (GEF 2009; MoEF, 2009; UNEP, 2011a; PU, 2012; UNDP, 2012; MoEF, 2013; Yong, 2013; GIZ, 2014; UNDP, 2014a-b; UNEP, 2014b), basically assuming 100 percent consumption of HCFCs in developing countries in 2005, except for mobile air conditioners and domestic refrigerators. Future fractions of HCFC in HFC/HCFC consumption have been made consistent with the phase-out schedule of HCFCs as described in the latest revision of the Montreal Protocol (UNEP, 2007) and with reported baselines[1] of parties, including updates based on later reporting of the parties to the UNEP Ozone Secretariat

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[1] 1989 HCFC consumption + 2.8% of 1989 consumption for non-Article 5 countries
Average of 2009 and 2010 for Article 5 countries

and the HCFC Phase-out Management Plans (HPMPs) of parties. The latter provide information on how much HCFC can be used by a given country in a given year – and the rest of the demand is assumed met through HFCs. We have made changes in the text of **Section 2.2** of the manuscript to make it clearer for the reader how HFC/HCFC shares were constructed.

2. *P. 4 L. 17: HFC-23 is not really a replacement compound. Please look for other compounds with high GWP.*

   Authors' Response: Although HFC-23 is primarily generated as a side-product of HCFC-22 production, it is also used directly in fire protection and integrated circuits or semiconductor industry. A small share of HFC-23 is also reported by parties to be used in commercial and industrial refrigeration sectors (UNFCCC, 2012). HFC-23 is therefore also a replacement compound to ODSs. In view of the above, we did not make any changes in the manuscript in response to this comment.

3. *P. 4 L. 25: the term PFPB is not explained*

   Authors' Response: Following the reviewer's advice, point feed prebake (PFPB) technology is now written out in full in the text in **Section 2.3** of the manuscript.

4. *P. 7 L 23: full abatement is not possible. In case of shut-down processes there are always emissions. In addition figures are mentioned further back in the results part. Maybe that could be done already here.*

   Authors' Response: Please note that "full abatement" does not necessarily mean that all emissions are removed, but merely that abatement technology is installed to the maximum technically feasible extent. How much emissions are removed will depend on the removal efficiency of the technology. In this case, post-incineration of HFC-23 is assumed to have a removal efficiency of 99.99% and accordingly that 0.01% of emissions will remain also under full abatement. To make this distinction clearer in the text, the sentence has been rewritten as: "HFC-23 emissions from HCFC-22 production are assumed fully equipped with post-combustion technology in OECD countries" in **Section 3.1** of the manuscript.

5. *P. 7 L. 28 the assumption that the CDM will go on in the future is not really realistic. EU for example has stopped the CDMs with HFC-23 and for example Miller et al. have increasing emissions in the future. Again, figures are mentioned further back in the results part. Maybe that could be done already here.*

   Authors' Response: Due to CDM, HFC-23 emissions from HCFC-22 production is controlled in most developing countries (except China where 36% is controlled). Since China is expected to produce 85% of global HCFC-22 in 2030, the rate of abatement adoption assumed for China after removal of CDMs is critical. Two core reasons are pointed out in an Ecofys study (Sachweh and Zhu, 2015) for why the abatement might continue also in the absence of CDM incentives. First, companies do continue running the abatement equipment, and in some instances even replace it with new equipment, to act in accordance to values defined under China's corporate social responsibility (CSR) policies. Second, the project operators in China anticipate future benefits from carbon market developments. This is reflecting the activity around carbon pricing in China, where, besides the China Certified Emissions Reduction (CCER) scheme, seven pilot emissions trading systems (ETSs) are in operation and a national ETS will be launched in 2017.

In addition, the Chinese State Council announced in May 2014 that it would strengthen domestic management of HFC emissions and accelerate the destruction and replacement of HFCs, focusing first on subsidizing the destruction of HFC-23, a powerful greenhouse gas that is the by-product of the manufacture of HCFC-22 (Finamore, 2015). According to the investment plan to support destruction of HFC-23 issued by the National Development and Reform Commission (NDRC) 2015 (NDRC, 2015; Schneider et al., 2015; Munnings et al., 2016), the Chinese government plans to introduce subsidies per tonne CO_2eq for implementation of new HFC-23 destruction devices for HCFC-22 production plants that are already in operation without support from CDM. According to personal information from Zhai (2016), a current subsidy per tonne CO_2eq emissions removed is ¥4, ¥3.5, ¥3, ¥2.5, ¥2, ¥1 in respective year 2014 to 2019. The subsidy will end in 2020. So the enterprises are already encouraged to report data about the production amount, destruction amount and new facility plans.

We consider the existence of this incentive scheme an indication of an interest from the Chinese government to continue to control emissions from this source also after 2020 when the subsidy is phased-out (it is after all a very cost-effective way to reduce greenhouse gases!). Given the subsidy scheme, we do not find it realistic to expect that plants currently equipped with control technology will actively remove it as support from CDM ceases. The current level of control implementation at 36% is therefore assumed sustained into the future. Finally, the Intended Nationally Determined Contributions (INDCs) submitted by China to the UNFCCC (UNFCCC, 2015 a-b) also aims to phase down emissive use of HCFC-22, a potent greenhouse gas, and to "achieve effective control" of HFC-23.

In addition to China, India announced during the 38th Meeting of the Open-Ended Working Group (OEWG 38) of the Parties to the Montreal Protocol in Kigali that its chemical industry must with immediate effect collect and destroy emissions of its most potent greenhouse gas, HFC-23 (Mahapatra, 2016). In view of the mentioned policy incentives, it appears most reasonable to assume that also without CDM developing countries will voluntarily continue destruction of HFC-23 emissions from HCFC-22 production as assumed in the GAINS baseline. To strengthen our argument here, we have added a brief description of the new policies/regulations to control HFC-23 emissions from HCFC-22 production in China and India in **Section 3.1** of the revised manuscript.

6. *P. 8 L. 9 the term (HSS/VSS is not explained*

   Authors' Response: Following the reviewer's advice, Horizontal Stud Söderberg (HSS) and Vertical Stud Söderberg (VSS) are explained in **Section 3.1** of the manuscript.

7. *P. 13 L 18ff. In the discussion, the following paper is missing. This contains additional information. Velders, G.J.M., S. Solomon, and J.S. Daniel, Growth in climate change commitments from HFC banks and emissions, Atmos. Chem. Phys., 14 (9), 4563- 4572, doi: 10.5194/acp-14-4563-2014, 2014. Furthermore, the Chapter 5 of the most recent Ozone Assessment (Harris and Wuebbles, 2014) (e.g. Figure 5-9) should also be part of the discussion.*

   Authors' Response: As far as we understand the work by Velders et al., it is more appropriate to refer to Velders et al. (2009) and Velders et al. (2015) as they are two fully different versions, whereas Velders et al. (2014), which is also referenced in Harris and Wuebbles (2014; p. 5.40), used an intermediate version that was a partial update of Velders et al. (2009).

8. *P. 15 L. 20 Authors do not mention that the F-gases will possibly be part of the Montreal Protocol. This should at least be mentioned in then conclusions. This will possibly change the whole cost model dramatically.*

   Authors' Response: According to the Kigali Amendment (KA) of the Montreal Protocol (MP) from October this year (i.e., well after the submission date of this paper), HFC consumption will be phased-down almost completely by 2050, with binding phase-down pathways specified for four different party groups. To facilitate the phase-down a Multilateral Fund (MLF) is to be set up and decided upon in the next meeting of the parties in October 2017.

   The fact that an agreement has now been met about the HFC phase-down paths does of course not change the cost model that we have used here. The cost analysis and its conclusions remain the same. However, depending on how the funds from the MLF will be distributed to different parties (which we will only know next year), the net cost burden will look different for different parties. In a separate forthcoming paper, we use the cost model described in this work to analyze the cost burden of different parties of the KA. Hopefully, it can bring insights that are useful for the meeting next year when the distribution of the MLF to different parties is to be decided upon.

   In **Section 3.1** of the manuscript, we have added the following text: "Note that the agreement to phase-down global use of HFCs outlined in the Kigali Amendment to the

Montreal Protocol during the 28th Meeting of the Parties in October 2016 (UNEP, 2016), was made after the submission date of this paper and has therefore not been considered in the baseline presented here. Its implications for emissions and costs will be the focus of a separate analysis."

9. *P. 30 Figure 9 is misleading. A lot of information is contained in other publications, if only the end point in 2050 is shown no real discussion is possible and the reader cannot really follow the discussion between the different scenarios.*

   Authors' Response: In the revised manuscript, we have included the RCP scenarios in our comparison in **Figure 10** of the revised manuscript using data from the IIASA-RCP database. Apart for the RCP scenarios (IIASA, 2009; Moss et al., 2010) and USEPA (2013) that provide data in five-year intervals until 2050 and 2030, respectively, the other referenced studies provide only one point in 2020 and one in 2050 without describing the pathway between these two points. We can therefore not display the paths between these points as they are not provided by the original source. We make a short clarifying note about this in the manuscript text of **Section 4.5**.

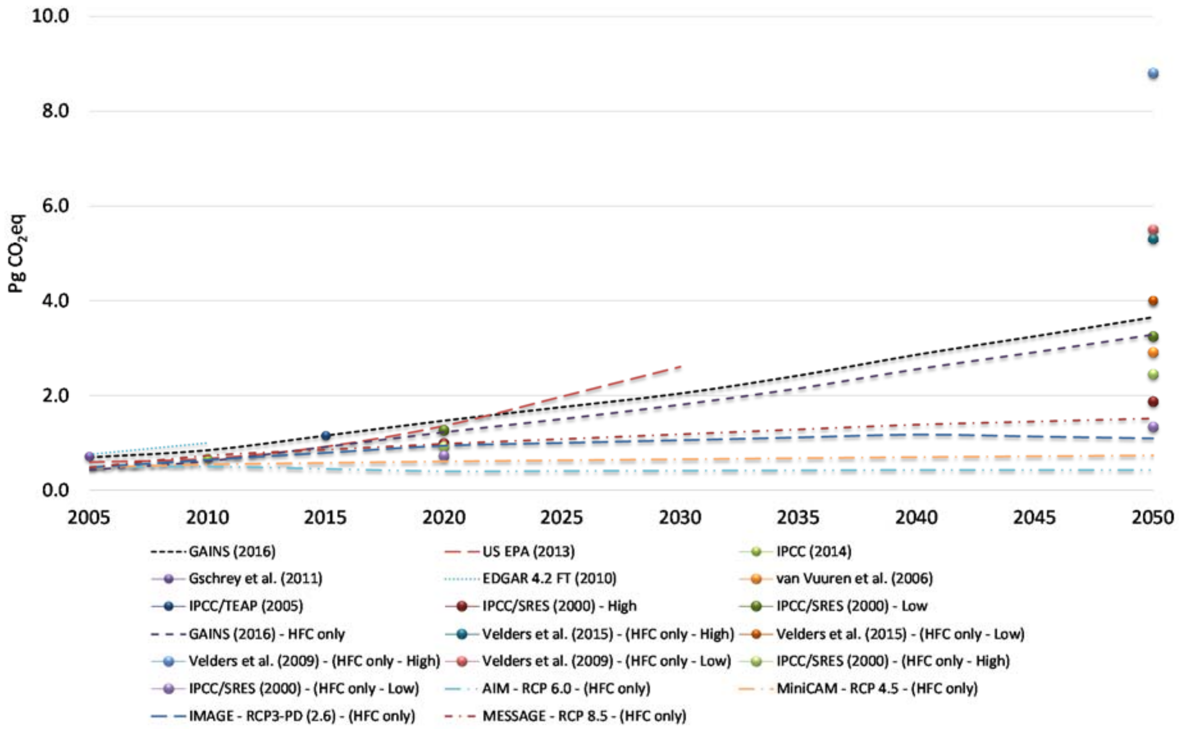

Figure 10: Comparison of GAINS baseline scenario with other F-gas business-as-usual scenarios

Referee #2 (L. Kuijpers)

From a study of the paper and its supplement on the analysis of emissions sources, abatement costs, and specific cost figures, the approach is in principle very much OK. However, there is one issue. The authors say that this publication builds further on other publications and they often refer to a small number of specific publications in the field, where there are many more, in my perception. Some questions therefore remain whether this publication brings the knowledge needed to a higher level, whether the overall conclusions are the right ones to draw for both developed and developing countries, emitting HFCs, PFC and SF_6*, whether there is not more quantitative to say on what could not be done (and how it could be done in future), and where that leaves us, or rather, what the authors perceive as the status to build further upon.*

Authors' Response: We thank Dr. Kuijpers for his comments and helpful suggestions on how to improve the manuscript. Below we provide detailed point by point replies to the questions. Referee comments are quoted in italics with authors' responses in blue.

We would have highly appreciated if the reviewer had provided references to the many publications he claims that we have missed. Further down in his review, he mentions a few references to UNEP reports that we had not referenced (except in one case). We have now added more references to various UNEP reports when appropriate (See: References).

1. *Approaches, ways of conducting the study of course, it is interesting to include in the analysis all kinds of HFCs, PFCs but also HCFCs. However, HCFCs are almost being phased out in developed countries, are being phased out in developing countries with strict guidelines for funding HCFC conversions. The inclusiveness of the HCFCs here, in this study, is still a bit beyond my understanding, in so far, what it exactly leads to in the analysis. Furthermore, one question here, is it known to the authors what is actually the case concerning how HCFCs are dealt with under the MP? Table S3 on page 17 (supplement) mentions that there are HCFC emission schedules as compliance issues. There are none, it is pure the consumption and production that is MP controlled (and is compliance oriented) and from which emissions have to be derived, which is (as noted by the authors) a very difficult task for the developing countries.*

   Authors' Response: Although phase-out of HCFCs is already addressed under the Montreal Protocol (MP) and therefore not a target of interest when analyzing future abatement efforts in the F-gases (HFCs, PFCs and SF_6), we still find it useful to keep track of and display baseline HCFC emissions in parallel to HFCs since they are very close HFC substitutes and with equally strong global warming potentials. We will, however, make it clearer to the reader that the HCFC reporting is only for the purpose of "keeping track" and not intended as a potential target for future abatement opportunities. We will also make sure to only consider HFCs, PFCs and SF_6 when referring to "F-gases", as we understand that this is the conventional meaning of the concept.

We have estimated the total refrigerant (HCFC/HFC) consumption at the sectoral level. For Annex-I countries (primarily non-Article 5 parties) HFC consumption in years 2005 and 2010 are taken as reported to the UNFCCC (UNFCCC, 2012). For non-Annex-I countries (i.e., primarily Article 5 parties), information on HCFC/HFC consumption by sector in years 2005 and 2010 is taken from available literature (GEF 2009; MoEF, 2009; UNEP, 2011a; PU, 2012; UNDP, 2012; MoEF, 2013; Yong, 2013; GIZ, 2014; UNDP, 2014a-b; UNEP, 2014b), basically for developing countries assuming for 2005 a 100 percent consumption of HCFCs, except for mobile air conditioners and domestic refrigerators. Future fractions of HCFC in HFC/HCFC consumption have been made consistent with the phase-out schedule of HCFCs in the latest revision of the Montreal Protocol (UNEP, 2007) and in consistency with the reported baselines[2] of parties, including updates based on later reporting of the parties to the UNEP Ozone Secretariat and the HCFC Phase-out Management Plans (HPMPs) of parties. The latter provide information on how much HCFC can be used by a given country in a given year – and the rest of the demand is assumed met through HFCs. We have made changes in the text of **Section 2.2** to make it clearer for the reader how HFC/HCFC shares were constructed. Thank you for pointing out the typological error in Table S3 of the Supplement. “Freeze in emissions” has been replaced with “Freeze in consumption”.

2. *Going to the conclusions, it mentions percentages for all kind of sectors, HFCs in RAC (HP?), foams, aerosols etc. But also HFC-23 and PFC and* SF_6*. Where PFC-*SF_6 *sectors are well reported to the UNFCCC, and certain reasonable estimates can be made for PFC emissions in developing countries in the so called baseline scenario defined here, there is another important issue. It is not the reporting of emissions from certain uses in the developed countries, but the lack of reporting by the developing countries where one states that there will be a growth of a factor of 5 or more in 40 years. In fact, of the non PFC-*SF_6 *and non-HFC-23 part so to say, RAC (and MAC) form 80% of the total consumption (and emissions?), definitely so in the developing countries. One can do a lot of precise analysis and apply all kinds of methods to derive abatement costs, but with these big unknowns, what is the overall (global) value of the conclusions? In fact this is already stated in section 2.2., activity data, where the references are limited that are related to UNEP, and in my opinion they are not always the most appropriate or up-to-date ones.*

Authors’ Response: It is correct that detailed reporting of consumption and emissions of F-gases is primarily available for developed countries and that the availability of directly reported information is more limited for developing countries. This is however exactly the reason why it is important to set up a model, which in a coherent way and on the basis of available information on known drivers for HFC, PFC, SF_6 consumption, is able to provide detailed sectoral estimates of regional F-gas emissions. E.g., on the basis of known drivers for HFC use in residential air conditioning (RAC) sector (i.e.,

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[2] 1989 HCFC consumption + 2.8% of 1989 consumption for non-Article 5 countries
Average of 2009 and 2010 for Article 5 countries

climate and income levels) and mobile air conditioning (MAC) sector (climate and growth in vehicle numbers by vehicle type), we conclude that 70% of baseline HFC emissions in developing countries (Article 5) in 2050 is expected to come from RAC and MAC sectors. For developed countries (non-Article 5), the share of emissions from RAC and MAC is found only 30%, while emissions from commercial, industrial and transport refrigeration was found to make up 70% in 2050.

The finding in GAINS that commercial and industrial refrigeration and refrigerated transport dominate HFC emissions from developed countries is consistent with the reporting of Annex I countries (which cover all major non-Article 5 countries) to the UNFCCC. We are aware that this is however not consistent with the finding presented by UNEP (TEAP XXVII/4 Task Force Report p.42 Figure 4-2, March 2016). In the UNEP report, HFC emissions from stationary air conditioning dominate historical and future HFC emissions in both developed and developing countries. Despite claims that UNEP baseline emissions are consistent with reported emissions to UNFCCC, we find that this is approximately correct for the total level, but not at the level of the individual sector contributions in non-Article 5 (nA5) countries. This unexplained inconsistency at the sector level between reported HFC emissions and the UNEP baseline emissions is a reason for not quoting this part of UNEP's work in our study. We could of course make a more explicit reference to this to make the reader aware of this inconsistency in UNEP's work, however, we consider reviewing UNEP's work outside the scope of this paper. In view of this, we did not make a reference to this particular UNEP report in the manuscript, however, references to other UNEP reports have been made when deemed appropriate.

3. *One comment, on the issue of the separation in regions, it is actually less important to have the regions very specific in the developed world (apart from maybe 3-5 regions), but they should be specific for the developing country world (not much of a detailed analysis). Efforts have been done by (Velders, 2015), but that activity is still ongoing. Lacking here is a much more specific analysis to regional approaches via bottom up calculation methods for R/AC such as in Ademe's RIEP model (by Clodic et al. in France), or in the USEPA vintaging model.*

   Authors' Response: The reviewer does not explain *why* he considers it more important to present regional results for developing countries in more detail than for developed countries. As we do full bottom-up estimations at the sector level for individual countries/regions, we can of course also present results in more detail. Following the reviewer's advice, we have now included one more graph (Figure 3 in the revised manuscript) showing the Baseline and MFR emissions by major world regions:

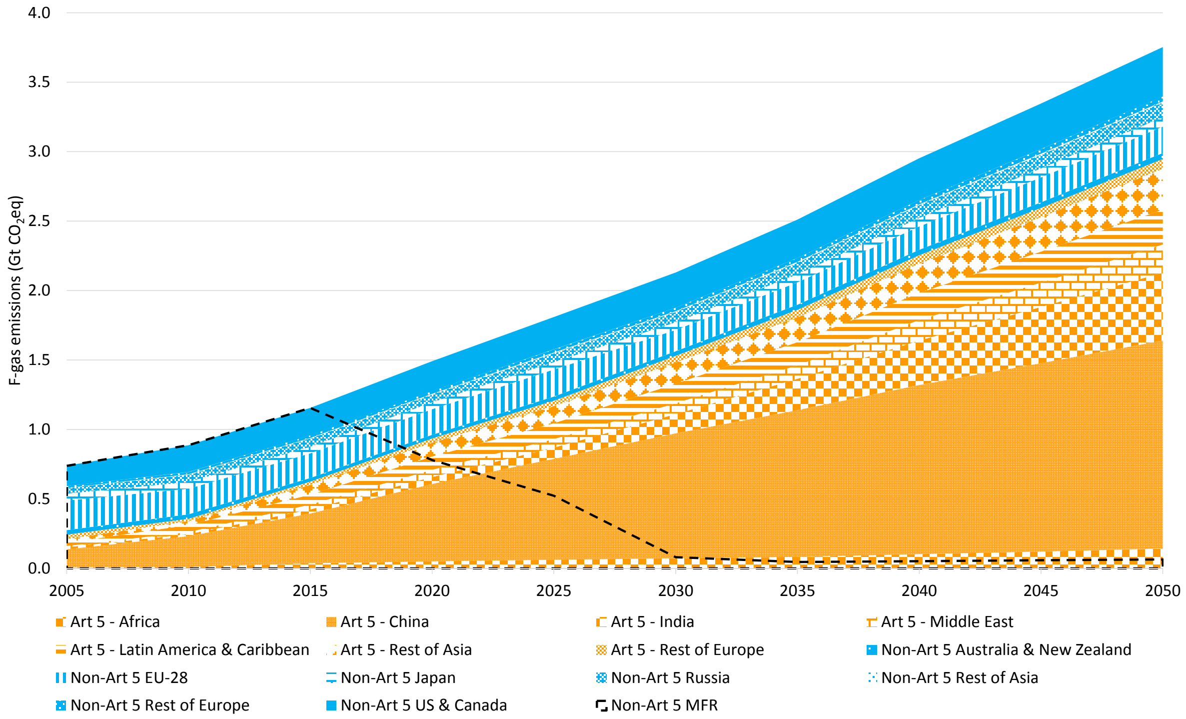

Figure 3: Baseline F-gas (HFCs, PFC and SF_6) emissions by major World regions (Article 5 in orange color and non-Article 5 countries in blue color).

4. *On the issue of the RAC and MAC sector, and the alternatives, and costs – Table S6 gives alternatives, but seems to be supported by a limited number of technical sources that deal with these, and does not present (in my opinion) a full scale of all options as should be presented in 2016.*

   Authors' Response: In the opinion of the reviewer we do not present a full scale of options for the RAC and MAC sectors. It would have been very useful if the reviewer had stated what options he is missing. In our opinion, we do cover all relevant alternatives (viz. alternative HFC's (i.e. HFC-32, HFC-152a, etc.), Hydrocarbons (i.e. HC-290, HC-600a etc.), CO_2, HFO-1234yf, NH_3) commercially available to HFCs in these sectors.

5. *Table S6 should be more underpinned with the references and the sort of statements made in those, in this way it has limited value - As an example also, the text as given on page 6, lines 5-15 on application of ammonia is a bit simplistic, too straightforward, there are many more issues involved, not only toxicity which seems to play no role - I also notice that a number of UNEP assessment and UNEP TEAP reports 2008-2016 are missing. Once one (1) reference (page 13, line 24) is made to a TEAP report (UNEP, 2009), but I cannot find that reference in the list, and there have been numerous (TEAP) reports after 2009, by the way –*

Authors' Response: UNEP (2009) is added in the reference section. We have added toxicity to the risks that must be considered when using ammonia in industrial refrigeration. We also provide a reference to a report by UNEP & SEPA (2010) on the alternatives in industrial refrigeration and UNEP (2015) on safe use of HCFC alternatives in refrigeration and air-conditioning. Following the suggestions of the reviewer, we have added a number of relevant UNEP sources in Table S6.

6. *Most questions are raised by Table S2 on page 4 of the supplement. It is not the issue that the GWP of HFC-134a in AR5 is NOT 1550 (but 1300), it also raises issues whether other GWPs have been used correctly (which are not always specified). No, it is in fact that for specific application sectors, the shares of certain (HCFC?) HFC refrigerants (say the share of certain sub-types of products) are assumed via a simple statement. Is this all coming from one reference source, is that enough, is that source up to date, do these values apply to developed and developing countries, are these values taken from one year, and will these be valid during the entire period up to 2050?*

Authors' Response: When comparing our results using AR4 GWPs to those using AR5 GWPs, we have for AR5 used the GWP over 100 years *with* climate–carbon feedback effects, as we noted that such had been made available in AR5 although they were not available in AR4 (IPCC AR5 WGI Section 8.SM.15, Table 8.SM.16 on p. 8SM-24: Metric Values for Halocarbons Including Climate–Carbon Feedback for Carbon Dioxide to Support Section 8.7.2 (http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/supplementary /WG1AR5_Ch08SM_FINAL.pdf). Hence, it is correct that for HFC-134a the GWP-100 without climate-carbon feedback effects is 1300 in AR5, but it is 1550 *with* climate-carbon feedback effects. The difference between these two values is due to indirect effects on warming when the substance is released to the atmosphere and exposed to other substances and variable conditions. As the values with climate-carbon feedback effects were made available in AR5, we consider it more appropriate to use these GWPs, since we are interested in the effect on global warming when these substances are released into the atmosphere. To make this clear to the reader, a note has been added in Table S2 that the GWPs taken from AR5 refer to values with climate-carbon feedback effects.

Regarding the comment that "…for specific application sectors, the shares of certain (HCFC?) HFC refrigerants (say the share of certain sub-types of products) are assumed via a simple statement", the reviewer is right that we should have been more specific about how these shares have been derived. We explain this in our answer to point 1 above. To make it clearer to the reader, we have added text the following text in **Section 2.2** of the revised manuscript: "In addition, for each HFC emission source, the fraction of HCFC in the HFC/HCFC use is identified from reported baselines of parties to the MP and modelled in consistency with the phase-out schedule of HCFCs in the latest revision of the MP (UNEP, 2007) and including later baseline updates reported by the parties to the UNEP Ozone Secretariat and in the HCFC Phase-out Management Plans (HPMPs) (GEF 2009; MoEF, 2009; UNEP, 2011a; PU, 2012; UNDP, 2012; MoEF, 2013; Yong, 2013; GIZ, 2014; UNDP, 2014a-b; UNEP, 2014b). These sources provide information on how much HCFC can be used by a given country in a given year – and the rest of the baseline demand is assumed met through HFCs."

We have also updated Table S2 to provide more precise information about sources used to determine the fractions of different types of refrigerants contributing to the consumption of HFCs and HCFCs, respectively. In the text, we have added the following clarification: "The second column of Table S2 shows assumptions made about the relative contribution of different refrigerant types given that the respective contributions from HCFCs and HFCs have been determined in consistency with the HCFC phase-out schedule under the MP. In the baseline, these assumptions apply globally and remain constant until 2050. Hence, over time only fractions of HFC/HCFC changes, while the relative contribution of different refrigerant types within these two groups remains constant."

Table S2. Sector specific contribution of different types of refrigerants and global warming potentials (GWPs) over 100 years used in GAINS

Sector	**Type and relative contribution of refrigerants (given HCFC/HFC fractions consistent with Montreal Protocol)**	**Sources used to determine relative contribution of refrigerants**	**Global warming potential over 100 years**		
			IPCC AR2 (1996)	**IPCC AR4 (2007b)**	**IPCC AR5 (2014)[a]**
Aerosol	HCFC-141b	MoEF (2009); UNEP (2011); GIZ (2014); UNDP (2014a-b)	713	725	782
	HFC-134a	Gschrey et al. (2011); UNFCCC (2012)	1300	1430	1550
Stationary air-conditioning[b]	HCFC-22	MoEF (2009); UNEP (2011); GIZ (2014); UNDP (2014a-b)	1780	1810	1760
	87% HFC-410A and 13% HFC-134a	Gschrey et al. (2011); UNFCCC (2012)	1670	2002	2018
Commercial refrigeration	HCFC-22	MoEF (2009); UNEP (2011); GIZ (2014); UNDP (2014a-b)	1780	1810	1760
	HFC-134a (25%)/ HFC-404A (70%)/ HFC-410A (5%)	Gschrey et al. (2011)	2693	3207	3237
Domestic refrigeration	HFC-134a	Gschrey et al. (2011); UNFCCC (2012)	1300	1430	1550
Fire extinguishers	Halon-1211/Halon-1301	MoEF (2009); UNEP (2011); GIZ (2014); UNDP (2014a-b);	4445	4515	4020
	HFC-236fa (50%)/HFC-227ea (47.5%)/HFC-23 (2.5%)	UNFCCC (2012)	4820	6805	6805
Ground source heat pumps	HCFC-22	MoEF (2009); UNEP (2011); GIZ (2014); UNDP (2014a-b);	1780	1810	1760
	HFC-410A	Schwartz et al. (2011)	1725	2088	1924

Industrial refrigeration	HCFC-22	MoEF (2009); UNEP (2011); GIZ (2014); UNDP (2014a-b)	1780	1810	1760
	HFC-134a (62%)/ HFC-404A (37%)/ HFC-23 (1%)	Gschrey et al. (2011)	2129	2486	2560
Mobile air conditioning[c]	HFC-134a	Gschrey et al. (2011); UNFCCC (2012)	1300	1430	1550
Refrigerated transport	HCFC-22	MoEF (2009); UNEP (2011); GIZ (2014); UNDP (2014a-b)	1780	1810	1760
	HFC-134a (80%)/ HFC-404A/ HFC-507 (18%)/ HFC-410A (2%)	Gschrey et al. (2011)	1661	1892	2363
Foam[d]	HCFC-141b	MoEF (2009); UNEP (2011); GIZ (2014); UNDP (2014a-b)	713	725	782
	HFC-134a (33%)/ HFC-245fa (61%)/ HFC-365mfc (5%)/ HFC-152a (1%)	Gschrey et al. (2011)	1098	1141	1181
Other HFC	HCFC-22	MoEF (2009); UNEP (2011); GIZ (2014); UNDP (2014a-b)	1780	1810	1760
	HFC-134a	UNFCCC (2012)	1300	1430	1550
HCFC-22 production	HFC-23		11700	14800	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					

[a] Note that GWPs taken from AR5 refer to GWPs over 100 years with climate-carbon feedback effects.

[b] Stationary air-conditioning includes both commercial and residential air-conditioning

[c] Mobile air-conditioning includes buses, cars, light and heavy duty trucks

[d] Foam includes both one component and other foams

[e] HCFC-22 production for both emissive and feedstock use

Referee #3 (A. McCulloch)

The paper is a result of very comprehensive modelling of the projected deployment of HFCs, PFCs and SF_6 *in each of their current end uses and each region of the world. This has involved the assembly of a large quantity of data and many assumptions. The end result is only as good as the quality of the data and assumptions and both of these need to be revisited if the work is to be of any value. I have not attempted a comprehensive review of the changes required and, while the following are intended as examples of shortcomings, they are not the only ones that need to be addressed.*

Authors' Response: We thank Dr. McCulloch for his comments and helpful suggestions on how to improve the manuscript. Below we provide detailed point by point replies to the questions. Referee comments are quoted in italics and authors' responses in blue.

We would have highly appreciated if the reviewer had explained the exact nature of the many shortcomings he is referring to. We can of course only respond to short-comings that the reviewer actually lists and not address comments that are not made more explicit by the reviewer.

1. *The values of the GWPs, quoted as being from AR5, in Table S2 are incorrect, particularly those for HFC-134a, the most widely used HFC, but also HFC-23, PFC 14 and SF6. This affects the numerical values of all of the results.*

   Authors' Response: No, the GWPs taken from IPCC AR5 and used in the report in Figure 12 as comparison to AR4 results (which were used for all estimations) are not incorrect, but correspond to GWPs over 100 years *with* climate–carbon feedback effects (IPCC AR5 Section 8.SM.15, Table 8.SM.16 on p.8SM-24: Metric Values for Halocarbons Including Climate–Carbon Feedback for Carbon Dioxide to Support Section 8.7.2, http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf). Hence, the reviewer is correct in so far that for HFC-134a the GWP-100 *without* climate-carbon feedback effects is 1300, but it is 1550 *with* climate-carbon feedback effects. The difference between these two values is due to indirect effects on warming when the substance is released to the atmosphere and exposed to other substances and variable conditions. Albeit not available with climate-carbon feedback effects in AR4, we consider it more appropriate to compare to the AR5 GWPs with feedback effects as these are available. After all, we are interested in the effect on global warming when these substances are released to the atmosphere. To make this distinction clearer to the reader, a note has been added in **Table S2** that the GWPs taken from AR5 refer to values with climate-carbon feedback effects.

2. *There seems to be an assumption in the models (or their inputs) that the industries using these materials are isolated regionally whereas in fact they are globalized. One result*

of this is that the prohibition of use of HFC-134a in mobile air conditioning (MAC) in Europe is considered not to affect its use in this application in the rest of the world. The reality is that manufacturers of original equipment are supra-regional and MAC systems that use HFC-134a have now, or shortly will be, superseded world-wide. The modelling needs to reflect the realities of the markets.

Authors' Response: We agree with the reviewer that the modelling should reflect the realities of the markets, but disagree on the conclusion he draws about how new technologies marketed worldwide can be expected to be taken up in the absence of further directed regulations (which is how we define our baseline). In the case of HFC-134a use in Mobile Air-Conditioners (MACs), the existing alternatives HFO-1234yf and CO_2-based systems are still relatively expensive compared with HFC-134a. Therefore, adoption of these technologies in new cars requires regulations that ban/tax/restrict the use of HFC-134a in MACs. To the extent that such regulations are currently in place (e.g., in the US, Canada, EU and Japan), the GAINS model assumes a phase-in of new alternatives in these markets, i.e., HFOs or CO_2-based technology (whichever has the lowest marginal cost -which happens to be HFO-1234yf in most markets). Does a phase-out of HFC-134a in MACs in these markets automatically lead to uptake also in other markets that do not have similar regulations in place as suggested by the reviewer? We do not think so and for the following reasons:

a. HFC-134a is currently considerably cheaper than HFO-1234yf. We therefore see no reason to believe that new cars sold to unregulated markets will use HFO-1234yf although it is readily available in the world market. A parallel can be made to the spread of catalytic converters, which is a technology that has been around for decades and used as standard in developed countries. Still, cars manufactured in industrialized countries but for export to African countries without legislation on catalytic converters, are frequently manufactured and delivered without catalytic converters (UNEP, 2012). Similarly, HFO technology availability on the world market will not be enough to spur uptake. Global uptake requires either that the price of the new technology is lower than the conventional technology or that regulations are put in place that force uptake of the more expensive technology.

b. Many countries have import bans on used cars (e.g., Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Venezuela, Uruguay) or restrictions that imported cars may not be more than 3 years old (e.g., Bolivia, India) or high import duties for used cars which severely hampers imports (e.g., Russia, China) (UNEP, 2011; Macias et al., 2013). New MAC technology can therefore not be expected to rapidly spread world-wide with export of used cars from regions with regulations in place. Exceptions may be Mexico and African countries. Mexico imports used cars from the US that may in the future be equipped with HFO-1234yf. Used cars exported from regulated regions to African countries may in the future be equipped with more expensive AC technology, however, it is questionable if these will be refilled with the relatively expensive HFO-1234yf if this is not required by regulations. The African market is however a very small fraction of the global car market.

In Section 3.1 of the manuscript we have explicitly mentioned that: "Due to the relatively high cost of HFO-1234yf compared to HFC-134a (Schwartz et al., 2011; Carvalho et al., 2014; USEPA, 2013; Purohit et al., 2016) and extensive import bans and restrictions on international trade with used cars (UNEP, 2011b; Macias et al., 2013), we consider it unlikely that new MAC technology will be taken up in the absence of directed regulations or spread globally through export of used cars from regions with regulations in place."

3. *On a similar note, there is little or no justification for assumptions such as that in lines 21 to 24 of page 11 that abatement of HFC-23 emissions from Chinese production of HCFC-22 will remain constant. While it might happen that no new HCFC-22 production will have HFC-23 treatment and disposal, this is by no means certain. This is such an important assumption that, if Feng et al. (2012) give reasons, they should be repeated in this paper.*

Authors' Response: HFC-23 emissions from HCFC-22 production is assumed controlled in most developing countries due to CDM (except China where 36% is controlled). Since China is expected to produce 85% of global HCFC22 in 2030, the rate of abatement adoption assumed for China in the baseline is critical. In China, the State Council announced in May 2014 that it would strengthen domestic management of HFC emissions and accelerate the destruction and replacement of HFCs, focusing first on subsidizing the destruction of HFC-23 from manufacture of HCFC-22 (Finamore, 2015). According to the investment plan to support destruction of HFC-23 issued by the National Development and Reform Commission (NDRC) 2015 (NDRC, 2015; Schneider et al., 2015; Munnings et al., 2016), the Chinese government plans to introduce subsidies per tonne CO_2eq for implementation of new HFC-23 destruction devices for HCFC-22 production plants that are already in operation without support from CDM. According to personal information from Zhai (2016), a current subsidy per tonne CO_2eq emissions removed is ¥4, ¥3.5, ¥3, ¥2.5, ¥2, ¥1 in respective year 2014 to 2019. The subsidy will end in 2020. Enterprises are already encouraged to report data about the production amount, destruction amount and new facility plans. We consider the existence of the policy efforts listed above together with the implemented incentive scheme, an indication of an interest from the Chinese government to continue to control emissions from this source also after 2020 when the subsidy is phased-out (it is after all a very cost-effective way to reduce greenhouse gases). We do not find it realistic to expect that plants currently equipped with control technology will actively remove it as the support from CDM ceases. The current level of control implementation at 36% is therefore assumed sustained into the future. We have added a description of new policies/regulation to control HFC-23 emissions from HCFC-22 production in China and India in **Section 3.1** of the revised manuscript.

4. *The paper contains a section on comparison with other studies but fails to mention the Representative Concentration Pathways used by IPCC to describe the future concentrations of all greenhouse gases. The baseline scenario given in this paper results in emissions between two and three times higher than the largest of the RCP scenarios (RCP8.5). At the very least this discrepancy needs to be addressed and sufficient reasons given to enable the scenario derived for this paper to be used in the broader context of future greenhouse gas emissions. Admittedly, the impact of the compounds covered by this paper amounts to less than 2% of the total impact of all greenhouse gases in the future, but although their effect is small, it is essential that it is placed accurately in the context of total greenhouse gas impacts.*

   Authors' Response: Yes, thank you this is a very good suggestion. We have now included the RCP scenarios in our comparison in **Figure 10** of the revised manuscript using data from IIASA's RCP database. In addition, in the Introduction (**Section 1**) we also relate the importance of F-gases to total anthropogenic greenhouse gas emissions as suggested.

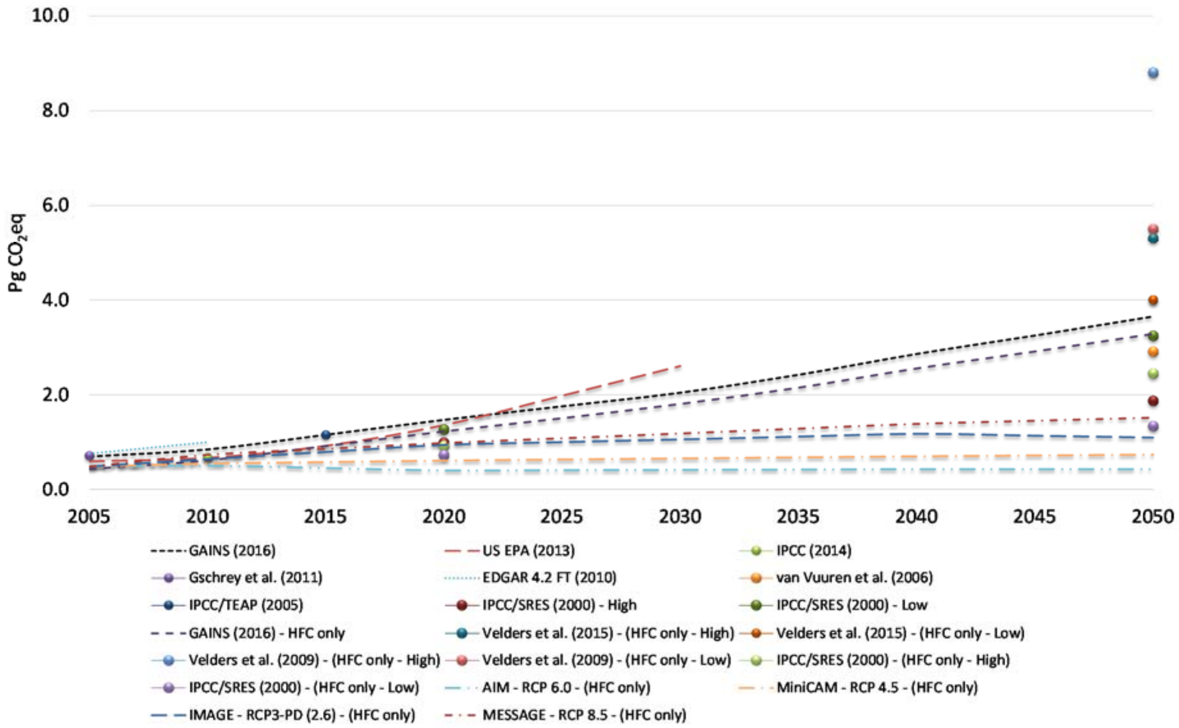

Figure 10: Comparison of GAINS baseline scenario with other F-gas business-as-usual scenarios

5. *Finally, the authors should avoid using percentages where absolute values would be more instructive. For example, the abstract states "Estimates show that it would be technically feasible to reduce F-gas emissions by 86 percent between 2018 and 2050". This percentage is influenced by both the baseline values and the projection. It would be far more instructive to quote the absolute values that is "from X Pg* CO_2*eq/yr to Z*

PgCO$_2$ eq/yr". Furthermore, the value quoted does not agree with the value scaled from Figure 3 (92%).

Authors' Response: As suggested, the percentage reduction in cumulative emissions between 2018 and 2050 mentioned in the abstract has now been replaced with absolute emission levels in the **Abstract** and **Section 4**. Please note that the statement of 86% refers to technically feasible cumulative removal of emissions compared to baseline emissions over the entire time period 2018 to 2050. Due to limitations in the short-run to immediately implement full technology adoption, the maximum cumulative reduction considered possible below baseline emissions is somewhat smaller than the relative reduction of 94% that we measure between the annual emission level in 2018 and the lowest annual (not cumulative!) emission level considered technically possible to achieve in 2050.

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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 (HFCs, PFCs and SF$_6$) emissions are estimated at 0.~~95~~7 Pg CO$_2$eq in 2005 with an expected increase to 3.7 Pg CO$_2$eq 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~~from 81 to 11 PgCO$_2$eq between 2018 and 2050. A reduction in cumulative emissions ~~by 72 percent~~to 23 Pg CO$_2$eq is estimated possible at a marginal abatement cost below 10 €/t CO$_2$eq. We also find that future F-gas abatement is expected to ~~be~~become relatively more costly for developing than ~~for~~ developed countries due to differences in the sector ~~distribution of~~contribution to emissions and abatement potentials.

1 Introduction

~~Many fluorinated~~Fluorinated greenhouse gases (F-gases) contribute approximately two percent of the global greenhouse gas emissions (IPCC, 2014). The rapidly increasing demand for refrigeration and cooling services, particularly in developing countries, threatens to increase F-gas emissions considerably over the next few decades. Many F-gases have very high global warming potentials (GWP~~), so~~) and therefore 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~~gains.iiasa.ac.at), we estimate in five-year intervals for 2005 to 2050 global emissions and abatement potentials of the F-gases (hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF$_6$)), which are addressed under the Kyoto Protocol (KP) (UNFCCC, 2014). To account for the full global warming effect of the combined use of HFCs and hydrochlorofluorocarbons (HCFCs) as coolants, and considering that they are close substitutes with equally strong GWPs, we keep track of and display baseline HCFC emissions in parallel to HFC emissions, even though HCFCs are not a target for future abatement efforts since they are addressed as ozone-depleting substances (ODS) that are subject to phase-out under the Montreal Protocol (MP) (UNEP, 2007). Twenty source sectors (14 for HFCs, 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~~adds to existing literature (Velders et al., 2009; Gschrey et al., 2011; Meinshausen et al., 2011; Montzka et al., 2011; USEPA, 2013; Velders et al., 2014; Ragnauth et al., 2015; Velders et al., 2015) ~~in that it provides information on both emissions~~an independently developed emission inventory with future projections and ~~costs~~abatement potentials estimated at the ~~sector and~~ technology level ~~and therefore enables~~, thereby allowing for a high degree of resolution ~~of~~for 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~~with comparisons to previous studies. Section 5 discusses different sources of uncertainty and Section 6 concludes the study. More details on ~~HCFC/HFC, PFC~~HFCs, PFCs 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~~2007a). Starting from April 2015, Annex-I (industrialized) countries report all greenhouse gases to the United Nations Framework Convention on Climate Change (UNFCCC) (~~2015~~UNFCCC, 2015a) using GWPs from IPCC AR4 (IPCC, ~~2007a~~2007b). 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~~make comparisons to the use of IPCC/AR2 (IPCC, ~~1997~~1996) 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~~second, 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:

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

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), HCFC/HFC consumption data is extracted from available literature (MoEF, 2009; UNEP, ~~2011~~2011a; GIZ, 2014; UNDP, 2014a-b). However, for ~~many~~some 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~~2015a). 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~~in the HFC~~ in~~/HCFC use is identified from reported baselines[1] of parties to the MP and ~~modeled following~~modelled in consistency with the phase-out schedule of HCFCs in the latest revision of the MP (UNEP~~ (~~, 2007~~).~~) and including later baseline updates reported by the parties to the UNEP Ozone Secretariat and in the HCFC Phase-out Management Plans (HPMPs) (GEF 2009; MoEF, 2009; UNEP, 2011a; PU, 2012; UNDP, 2012; MoEF, 2013; Yong, 2013; GIZ, 2014; UNDP, 2014a-b; UNEP, 2014a-b). These sources provide information on how much HCFC can be used by a given country in a given year – and the rest of the baseline demand is assumed met through HFCs. 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~~derive 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~~aluminium and magnesium. Activity data for 2005 and 2010 production of primary ~~aluminum~~aluminium 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~~aluminium production data is obtained from the GAINS Asia project (Amann et al., 2008; Purohit et al., 2010). Although HFC-23 is primarily 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~~).~~), it is also used directly in fire protection and integrated circuits or semiconductor industry. A small share of HFC-23 is also reported by parties to be used in commercial and industrial refrigeration sectors (UNFCCC, 2012). Production levels are reported for historical years (UNEP, ~~2014~~2014c) 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).

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[1] 1989 HCFC consumption + 2.8% of 1989 consumption for non-Article 5 countries
Average of 2009 and 2010 for Article 5 countries

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, 2016) 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~~aluminium 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 point feed prebake (PFPB) technology 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~~aluminium smelters of 0.7 tonne CO_2eq~~/~~ per tonne Al produced is used in this study, while the global PFPB technology average of 0.27 tonne CO_2eq~~/~~ per 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~~ per tonne Mg is used for China (Fang et al., 2013) and a default value (1.0 kg SF_6~~/t~~ per tonne 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:

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

~~Where~~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):

$$p_{it}^{electr} = 3 + 2\, p_{it}^{gas} \qquad (3)$$

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:

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

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:

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

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~~; Zaelke and Borgford-Parnell, 2015; UNEP, 2016a). We have included monetary benefits accrued to increased energy efficiency. Some alternative substances are known to be flammable and/or toxic 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~~a given sector. Transaction costs, e.g., the one-time cost of training staff in the use of a different ~~substance~~substances 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.~~is toxic and has flammable properties (UNEP & SEPA, 2010 p.25). Another important consideration for NH_3 is its propensity for corrosion and its affinity for moisture (UNEP, 2015 p.46). On the other hand, NH_3 is, and has for decades been, widely used in industrial refrigeration, which proves that its toxicity and 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~~take into account the effects on emissions from implementation of existing legislation ~~currently adopted~~ to control F-gas emissions at the regional or national level ~~based on~~as stated in publicly available information~~.~~ and summarized in 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-wide 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~~also 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 and a few other sectors starting from January 2015 and also ~~contains~~containing 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 the 2014 ~~levels.~~level (Capros et al., 2016). 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 comprehensive 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-wide legislation~~,~~ and are more stringent~~,~~ and address more specific sources than the EU-wide 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~~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~~2014d). 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). Note that the phase-down of the global use of HFCs agreed in the Kigali Amendment to the Montreal Protocol during the 28th Meeting of the Parties in October 2016 (UNEP, 2016b), was not available at the submission date of this paper and has therefore not been considered in the baseline analysed here. Its implications for emissions and costs will be the focus of a separate analysis.

Due to the relatively high cost of HFO-1234yf compared to HFC-134a (Schwartz et al., 2011; Carvalho et al., 2014; USEPA, 2013; Purohit et al., 2016) and extensive import bans and restrictions on international trade with used cars (UNEP, 2011b; Macias et al., 2013), we consider it unlikely that new MAC technology will be taken up in the absence of directed regulations or spread globally through export of used cars from regions with regulations in place.

HFC-23 emissions from HCFC-22 production are assumed fully ~~controlled~~equipped with post-combustion technology 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)[2] projects on global HFC-23 emissions for this sector. In this analysis we assume~~the Clean Development Mechanism (CDM)[3] projects on global HFC-23 emissions for this sector. HFC-23 emissions from HCFC-22 production are assumed controlled in

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~~[2] 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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most developing countries due to CDM, except China where 36 percent HCFC-22 production is controlled (Feng et al., 2012). According to the investment plan to support destruction of HFC-23 issued by the Chinese National Development and Reform Commission (NDRC) 2015, the Chinese government plans to introduce subsidies per tonne CO_2eq for implementation of new HFC-23 destruction devices for HCFC-22 production plants that are already in operation without support from CDM (NDRC, 2015; Schneider et al., 2015; Munnings et al., 2016). According to personal information from Zhai (2016), a current subsidy per tonne CO_2eq removed is ¥4, ¥3.5, ¥3, ¥2.5, ¥2, ¥1 in respective year 2014 to 2019. The subsidy will end in 2020. Therefore, the enterprises are already encouraged to report data about production and destruction amounts and new facility plans. Together with the other mentioned regulations, we consider the existence of this incentive scheme an indication that the Chinese government is interested in continued control of emissions from this source also after 2020 when the subsidy is phased-out. The Intended Nationally Determined Contributions (INDCs) submitted by China to the UNFCCC (UNFCCC, 2015b) in preparation of the Paris Agreement (UNFCCC, 2015c) also aims to phase-down use of HCFC-22 and to “achieve effective control” of HFC-23. Moreover, India announced during the 28th Meeting of the Open-Ended Working Group (OEWG 38) of the Parties to the Montreal Protocol that its chemical industry, with immediate effect, must collect and destroy emissions of HFC-23 (Mahapatra, 2016). Therefore, we assume in this analysis that the impact of CDM on emissions from HCFC-22 production in developing countries remains at the current level also 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 technologies, and multilateral agreements to phase down HFCs (~~UNFCCC, 2014).~~Fekete et al., 2015). 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 Horizontal Stud Söderberg (HSS~~/~~)/Vertical Stud Söderberg (VSS) or prebake technologies to ~~Point Fed Prebake (~~PFPB~~)~~ technology. According to the 2013 Anode Effect Survey of the International Aluminium Institute (IAI, 2014), 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~~,~~ and by almost 90 percent since 1990. With primary ~~Al~~aluminium production having grown by over 150 percent over the same period, absolute emissions of PFCs ~~by~~from the ~~Al~~ industry have been reduced from ~~approximate~~approximately 100 Tg ~~of~~ CO_2eq in 1990 to 32 Tg ~~of~~ CO_2eq in 2013 (IAI, 2014). In EU-28, emissions from primary ~~Al~~aluminium production are regulated under the EU-ETS system~~ and control options with ~~. As the marginal ~~costs falling~~cost of a switch to PFPB technology falls 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~~assumption is that with the natural turn-over of capital, all EU member states will have phased-in PFPB technology by 2020~~.~~ (Höglund-Isaksson et al., 2016). Primary ~~Al~~aluminium production in China is estimated at 55 percent of the global production capacity of 58.3 Mt in 2015 (USGS, 2016) ~~where~~and with almost all ~~primary Al~~ production facilities ~~are~~ employing ~~the~~ PFPB technology (Hao et al., 2016). For other non-EU~~-28~~ regions, current technology used in primary ~~Al~~aluminium smelters ~~will use~~is in the baseline ~~production technologies~~assumed to remain 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~~a 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 a few companies in a country (Tohka, 2005) and as the amount of PFC ~~use~~used allows for deriving the production volumes, data on PFC use ~~are~~is often confidential. Therefore GAINS uses ~~the volume of~~ PFC emissions reported to UNFCCC (2012) as activity ~~variable~~data 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~~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, 2016).

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~~-~~ to 10 percent depending on models (Daikin, 2016). For air-conditioning, removal efficiency when switching to HFC-32 is taken to be 68 percent for room air conditioners. Similarly, removal efficiency when switching to HFC-152a is ~~more than~~taken to exceed 90 percent in foam, non-medical aerosol and other applications~~.~~ (see Table S6 of the Supplement for references).

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~~%~~ percent for mobile air-conditioning and aerosol/foam sectors~~.~~ (see Table S6 of the Supplement for references).

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~~combined with ~~air and steam~~thermal oxidation of the gas through incineration. 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 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.~~), but can technically be reduced below 1 percent (IPCC/TEAP, 2005). 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 for aluminium smelters 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~~aluminium production technologies (VSS, SWPB and CWPB) to PFPB technology is more than 85 percent whereas retrofitting has a removal efficiency of ~~approximately~~about 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 assumed 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~~completely remove SF_6.

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~~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~~USEPA, 2016).

3.1 Politically feasible reduction scenarios

The baseline and the MFR scenarios define the upper and lower technical boundaries for the estimated 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~~t CO_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 (HFCs, PFCs and SF$_6$) emissions to global warming are estimated at 0.~~95~~7 and ~~1.14~~0.89 Pg CO$_2$eq, respectively, ~~whereof the~~ and with an additional 0.28 and 0.26 Pg CO$_2$eq 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$_2$eq, respectively~~ in ~~2005 and 2010.~~the respective years. In 2010, ~~32~~34.6 percent of ~~these~~F-gas emissions are released as HFCs from stationary air conditioning and refrigeration, ~~15~~13.6 percent as HFC-134a from mobile air conditioners, ~~19~~18.6 percent as HFC-23 emissions from HCFC-22 production for emissive and feedstock use, ~~8~~7.7 percent as HFCs from use in aerosols, foams, solvents, fire-extinguishers, ground-source heat pumps, ~~14~~12.9 percent as SF$_6$ from high- and mid- voltage switches, magnesium production, soundproof windows and other minor sources, and ~~13~~12.5 percent as PFCs from primary aluminium production and semiconductor industry.

Baseline ~~HFC, PFC and SF$_6$~~F-gas 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 an 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.

As shown in Figure 3, rapid growth in emissions is expected in Article 5 (developing) countries. With approximately seven-fold increases from 2010 to 2050, China is expected to contribute 39 percent of global F-gas emissions in 2050 followed by India (13 percent). For EU-28, F-gas emissions in 2050 will be lower than the 2005 level due to stringent F-gas controls whereas in USA and Canada emissions are expected to increase by a factor of two in the baseline scenario.

4.2 The future technical abatement potential

Figure ~~3~~4 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.

4.3 The cost of future technical abatement potentials

Figure ~~4~~5 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~~6 shows that global annual cost-savings from these options are estimated at over 15 billion Euro in 2050. The upper part of Figure ~~5~~6 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~~7 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~~-~~ to 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~~8 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$_2$eq of F-gases, while the expected contribution from non-Article 5 countries is~~ expected to release~~ 19 Pg CO$_2$eq over the entire period. With climate policies implemented globally and corresponding in stringency to a carbon price of 10 €/~~tCO$_2$eq~~t CO$_2$eq, the cumulative release over the entire period is estimated at 17 Pg CO$_2$eq from Article 5 countries and 6 Pg CO$_2$eq from non-Article 5 countries. ~~Hence, globally~~Globally, this means a reduction in cumulative F-gas emissions from 81 to 23 Pg CO$_2$eq over the period 2018 to 2050, i.e., a reduction in global cumulative emissions by 72 percent.

Figure ~~8~~9 shows the estimated total cost of achieving the respective cumulative emission reductions shown in Figure ~~7. As shown, non~~8. Non-Article 5 (i.e., primarily 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 mobile air conditioning and 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$_2$eq. For developing countries, with relatively limited contribution of emissions from industrial refrigeration and relatively large emissions from industrial processes and mobile air conditioning, the net cumulative abatement cost is higher and turns positive already at a carbon price of 40 €/t CO$_2$eq.

4.5 Comparison to other studies

Figure ~~9~~10 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; Meinshausen et al., 2011; Velders et al., 2009, 2014, 2015) that in year 2005 emissions of HFCs, PFCs and SF$_6$ contributed about 0.7 Pg CO$_2$eq 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~~–~~ to 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$_2$eq in 2050, is somewhat lower than the business-as-usual estimates of 4 to 5.4 Pg CO$_2$eq in 2050 by Velders et al. (2015) and Gschrey et al. ~~(2011).~~(2011), and significantly higher than in the Representative Concentration Pathways (RCPs) scenarios (IIASA, 2009). The reason for the difference in projected emissions can be sought in the use of different drivers. Just like this study uses sector-specific drivers (e.g., growth in commercial or industry value added), Gschrey et al. (2011) apply sector-specific assumptions to drive future trends in emissions. However, where we use regions-specific drivers based on macroeconomic scenarios by IEA-ETP (2012) and Capros et al. (2013), Gschrey et al. (2011)

make fixed assumptions for developed and developing countries, respectively, for short and long-term emission growth rates at the sectoral level. 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.~~2012; IIASA, 2012) as drivers for F-gas emissions.~~ 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 EU F-gas regulation~~ of the European Union~~, and therefore differences in the level of regulation should not contribute to differences in future emissions. ~~The~~Our baseline, as well as the most recent business-as-usual scenario from Velders et al. (2015~~) and the GAINS baseline presented here~~), project ~~almost twice the~~ higher global F-gas emissions in 2050 than ~~the SRES B1 family~~any of the different IPCC Representative Concentration Pathways (RCP) scenarios (~~1.9 Pg CO_2eq), that emphasises global solutions~~IIASA, 2009; Moss et al., 2010). In comparison 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~~our baseline emissions in 2050, the RCP scenarios are between 59 to 88 percent lower. 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 (2015a). Another reason may be differences in the sector-specific GWPs used. ~~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. Apart for RCP scenarios and USEPA (2013) that provide data in five-year intervals until 2050 and 2030, respectively, the other referenced studies provide only one point in 2020 and one in 2050 without describing the pathway between these two points.

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~~11 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.

Also note that GWP values are being continually revised to reflect current understanding of the warming potentials of CO_2 ~~and~~relative other greenhouse gases. Figure ~~11~~12 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 the most recent ~~GWP values~~GWPs stated with climate-carbon effects (IPCC, ~~2013~~2014) 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~~Many 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$_2$eq. 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$_2$eq.~~ 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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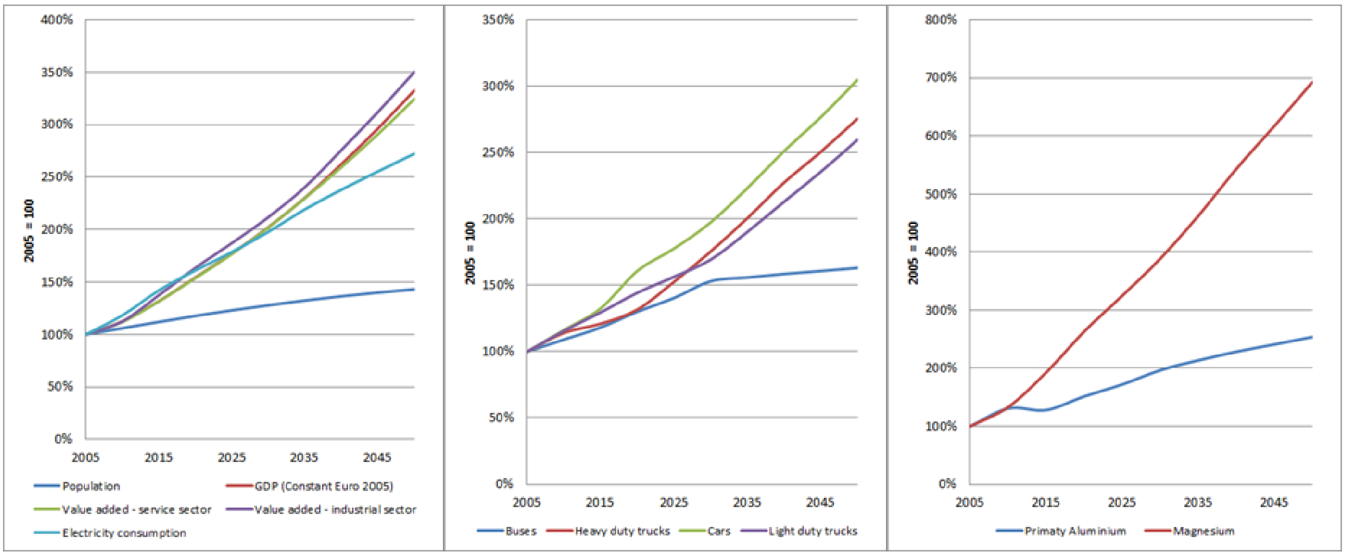


Figure 1: Global development 2005–2050 in major drivers for F-gas emissions entering model estimations from external sources

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

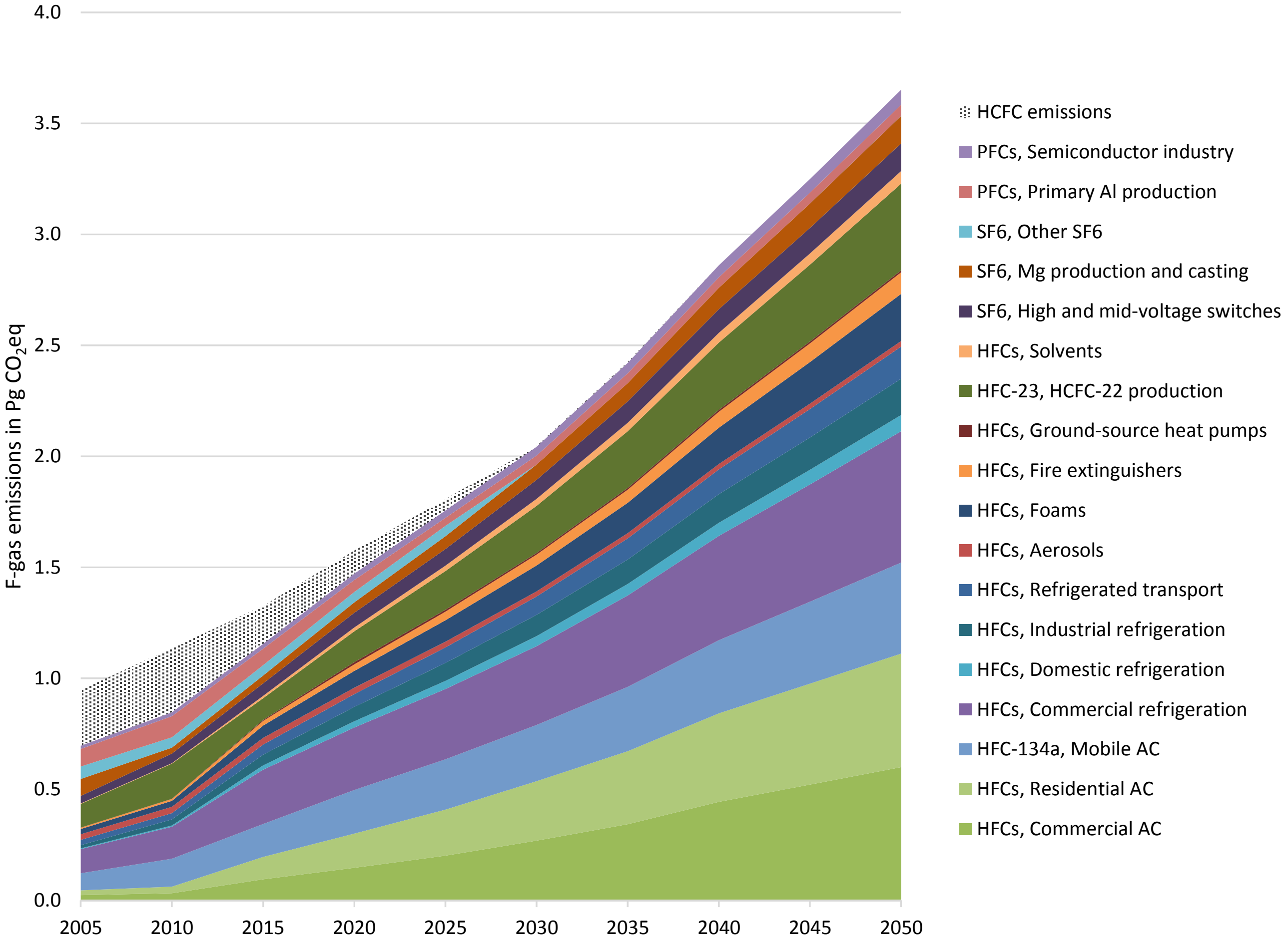


Figure 2: Baseline emissions of F-gases (~~HCFCs,~~ HFCs, ~~SF_6~~PFCs and ~~PFC~~SF_6) 2005 to 2050 by source sector. To facilitate comparison to other studies only reporting HFCs, ~~SF_6~~PFCs and ~~PFCs~~SF_6, the HCFC emissions are summed up at top of the graph.

~~**Figure 3**~~

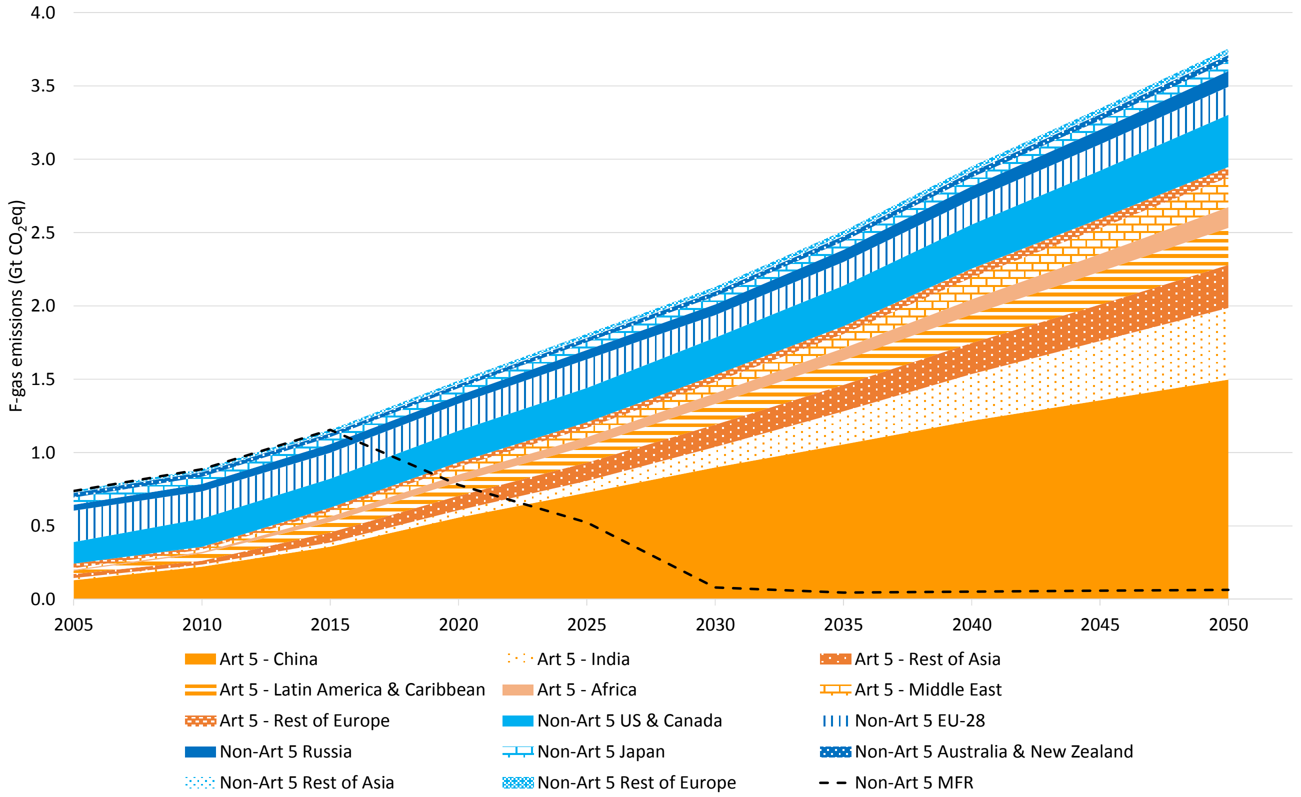


Figure 3: Baseline F-gas (HFCs, PFCs and SF_6) emissions by major World regions.

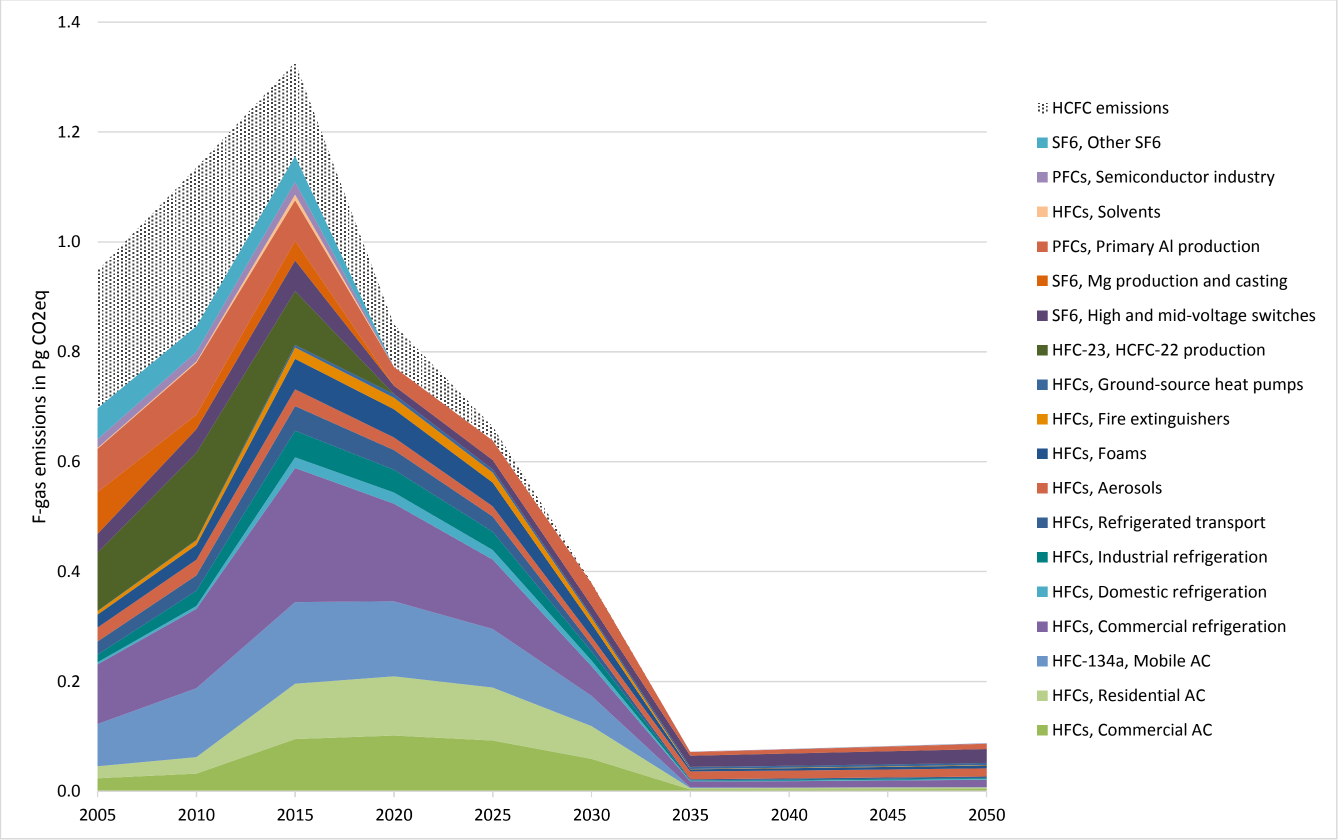


Figure 4: F-gas emissions in MFR scenario, i.e., after maximum technically feasible reduction 2020 to 2050.

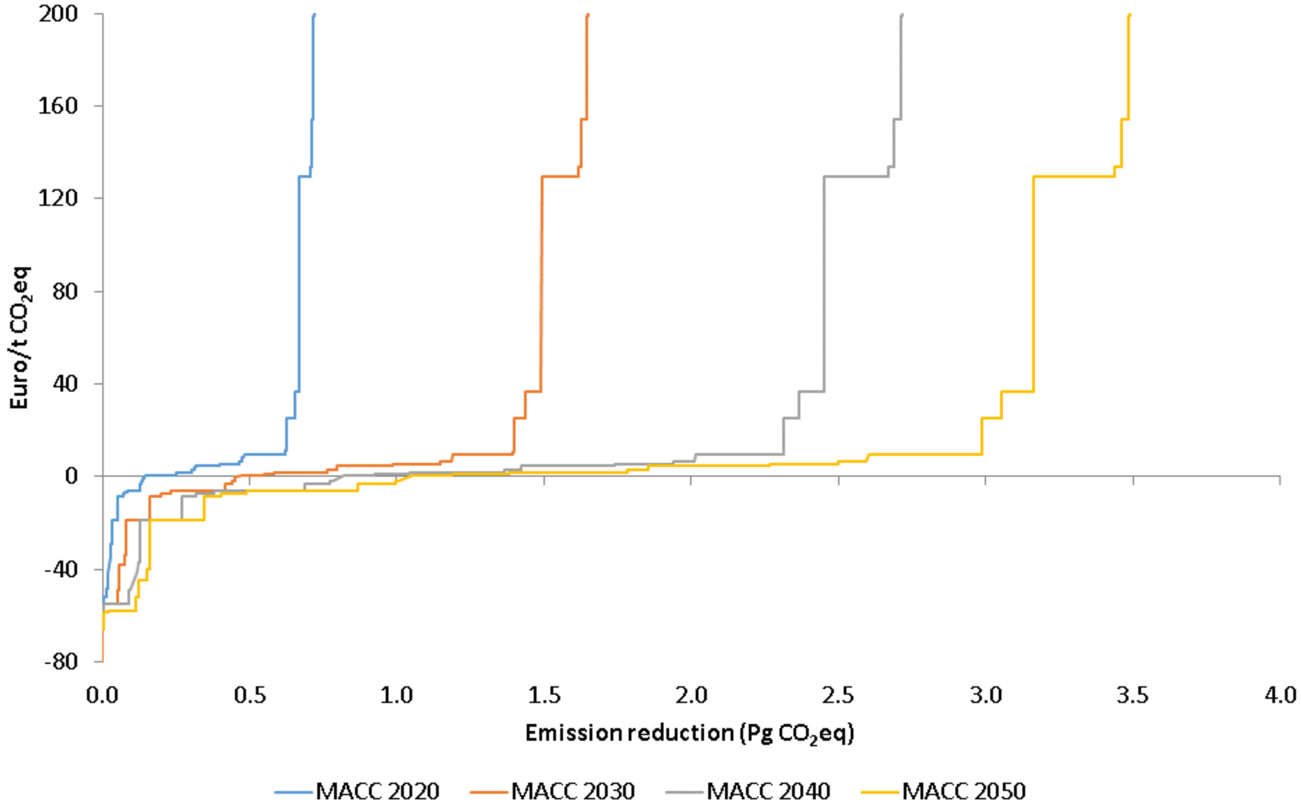


Figure ~~4~~5: Marginal abatement cost curves in 2020, 2030, 2040 and 2050 for reducing global emissions of F-gases.

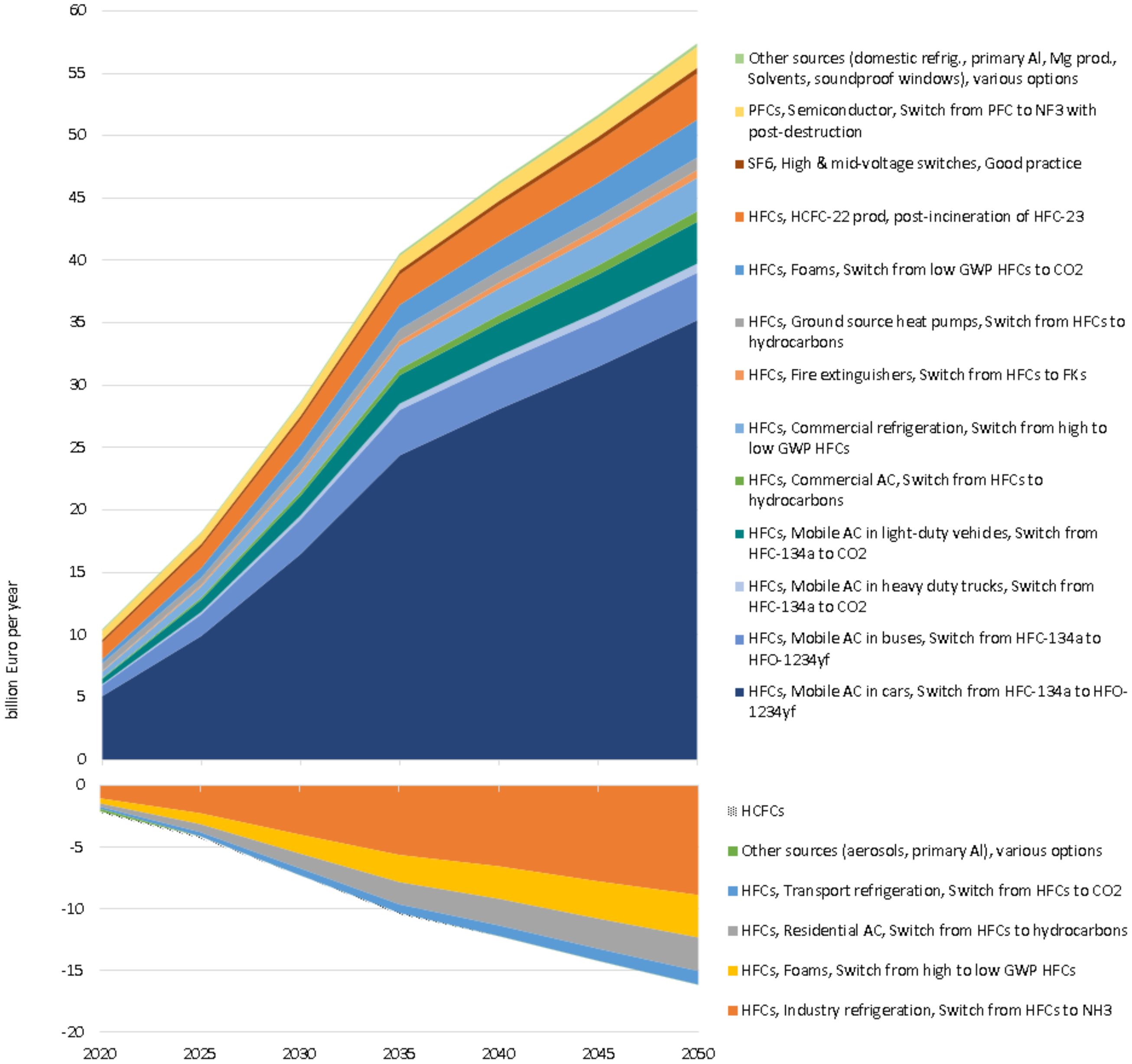


Figure ~~5~~6: Total annual costs by control option for implementation of abatement options found available at a marginal cost below 200€/tCO$_2$eq (corresponding to 98 percent of MFR abatement potential).

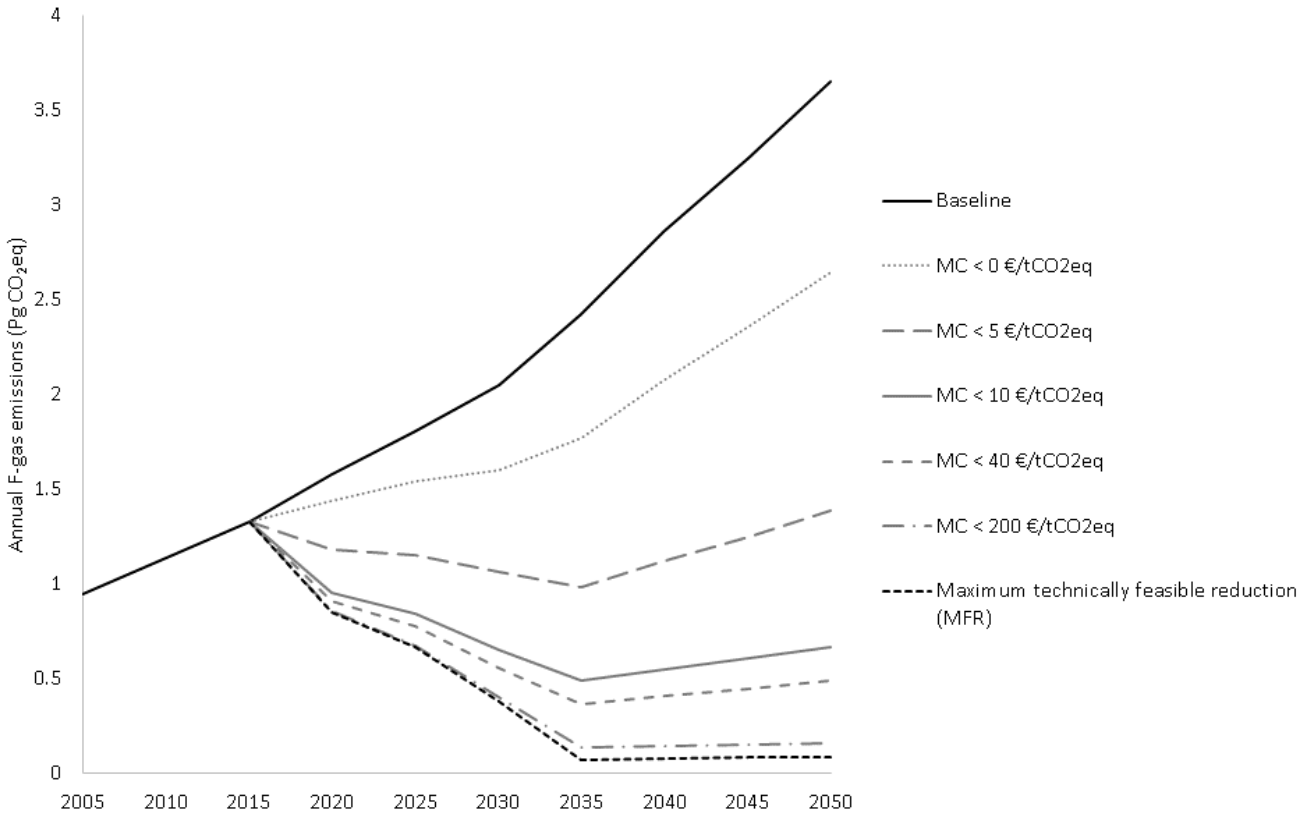


Figure ~~6~~7: Estimated emission pathways for F-gas emissions ~~(HFCs/HCFCs, PFCs, SF$_6$)~~ at different carbon price levels.

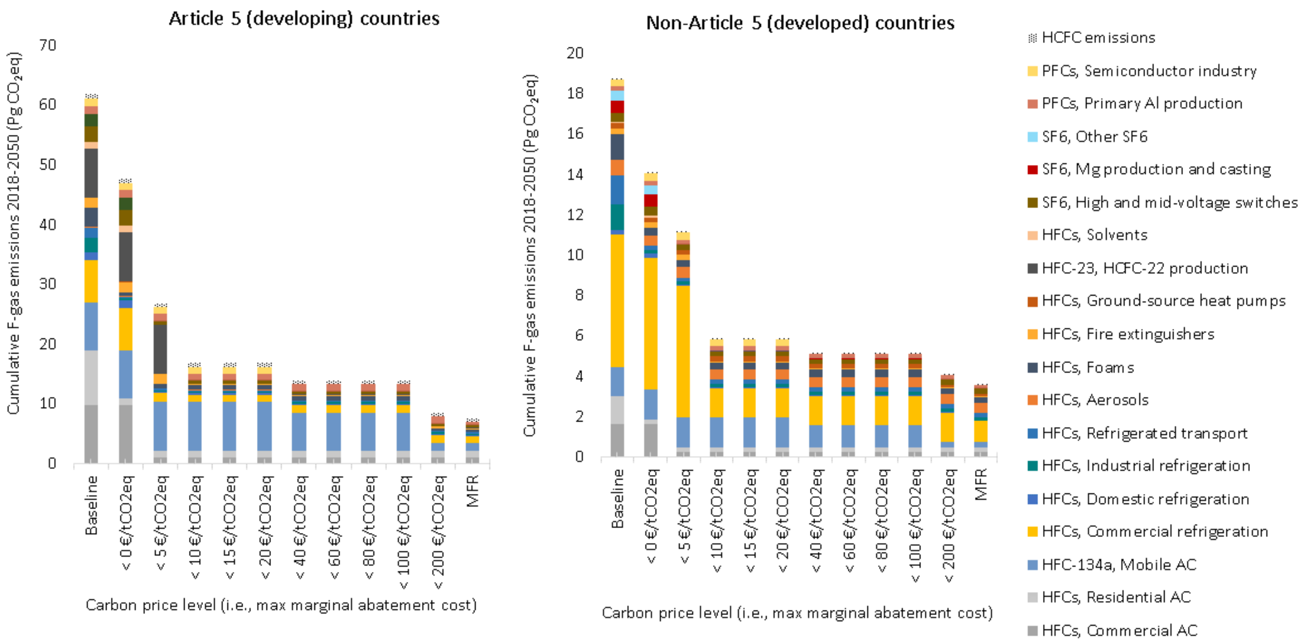


Figure ~~7~~8: Estimated cumulative F-gas emissions released over the period 2018-2050 at different carbon price levels in Article 5 (developing) countries and ~~Non~~non-Article 5 (developed) countries.

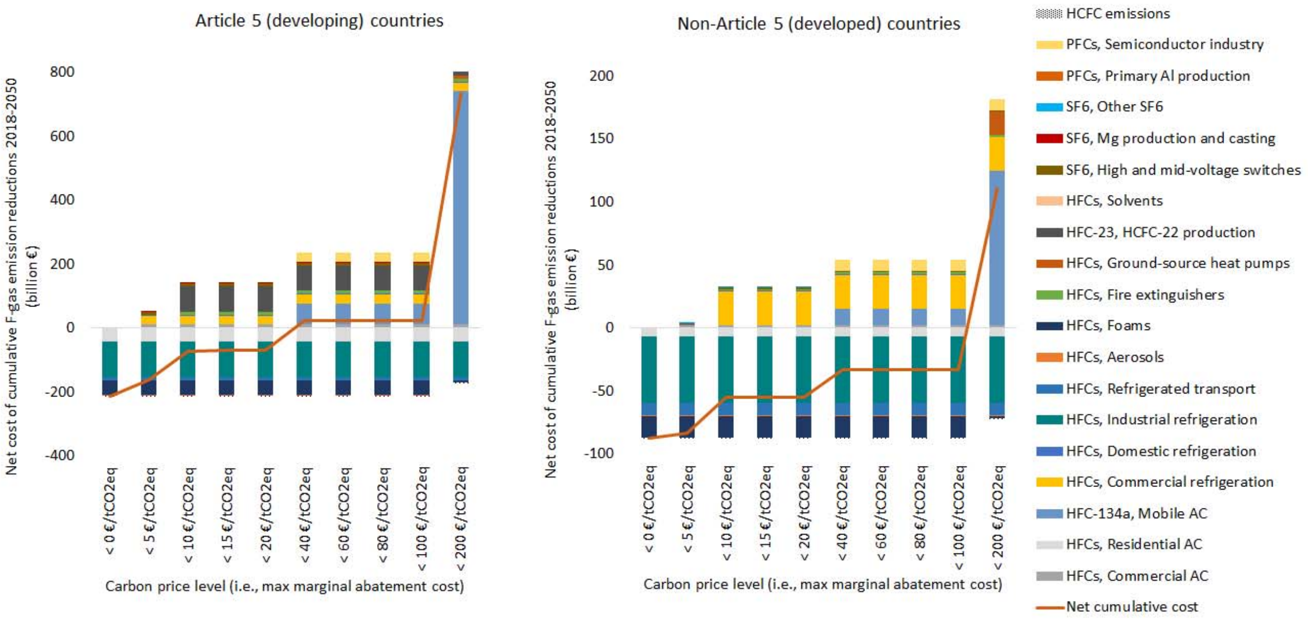
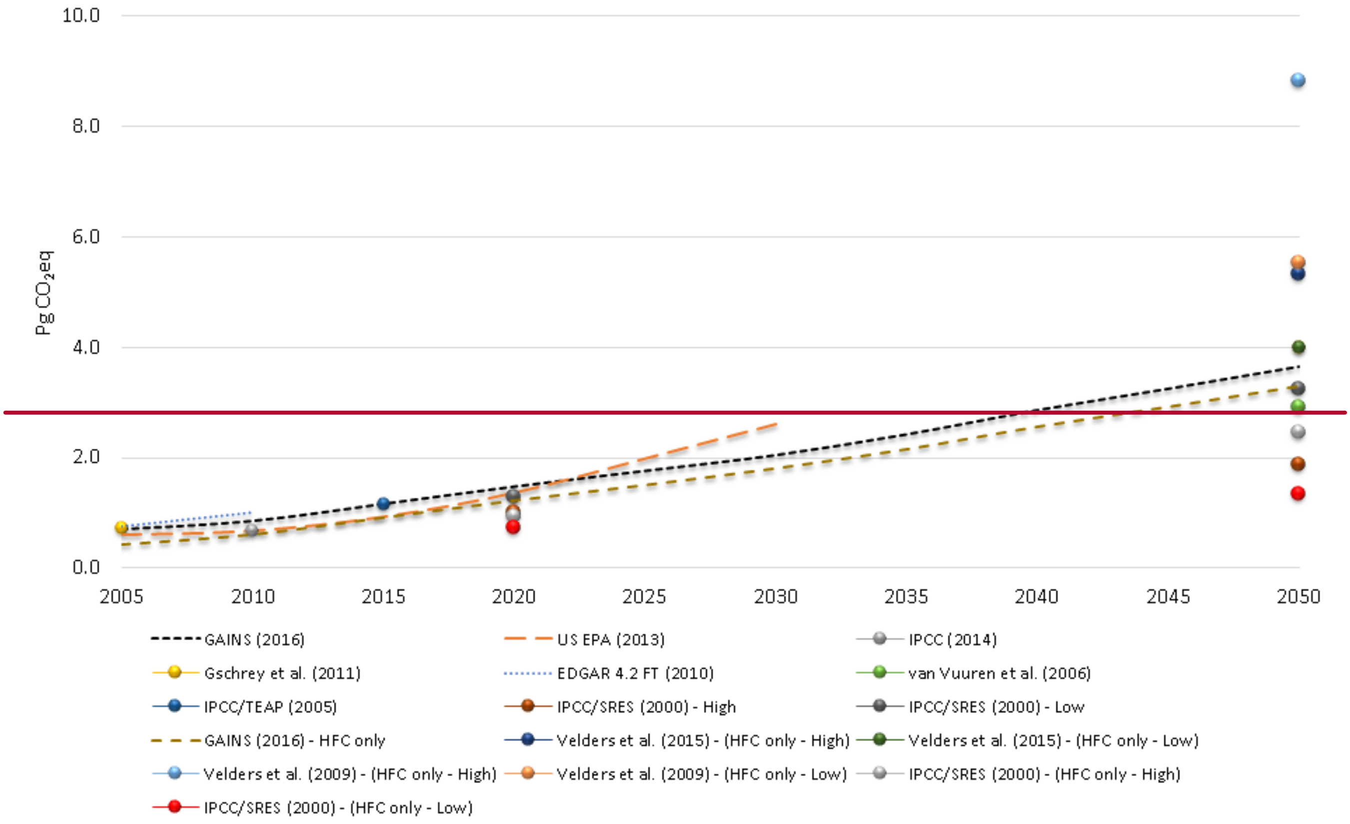


Figure ~~8~~9: Net costs of cumulative reductions in F-gas emissions over the period 2018-2050 at different carbon price levels in Article 5 (developing) countries and Non-Article 5 (developed) countries.


10.0
8.0
6.0
4.0
2.0
0.0
Pg CO$_2$eq
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
GAINS (2016)
US EPA (2013)
IPCC (2014)
Gschrey et al. (2011)
EDGAR 4.2 FT (2010)
van Vuuren et al. (2006)
IPCC/TEAP (2005)
IPCC/SRES (2000) - High
IPCC/SRES (2000) - Low
GAINS (2016) - HFC only
Velders et al. (2015) - (HFC only - High)
Velders et al. (2015) - (HFC only - Low)
Velders et al. (2009) - (HFC only - High)
Velders et al. (2009) - (HFC only - Low)
IPCC/SRES (2000) - (HFC only - High)
IPCC/SRES (2000) - (HFC only - Low)

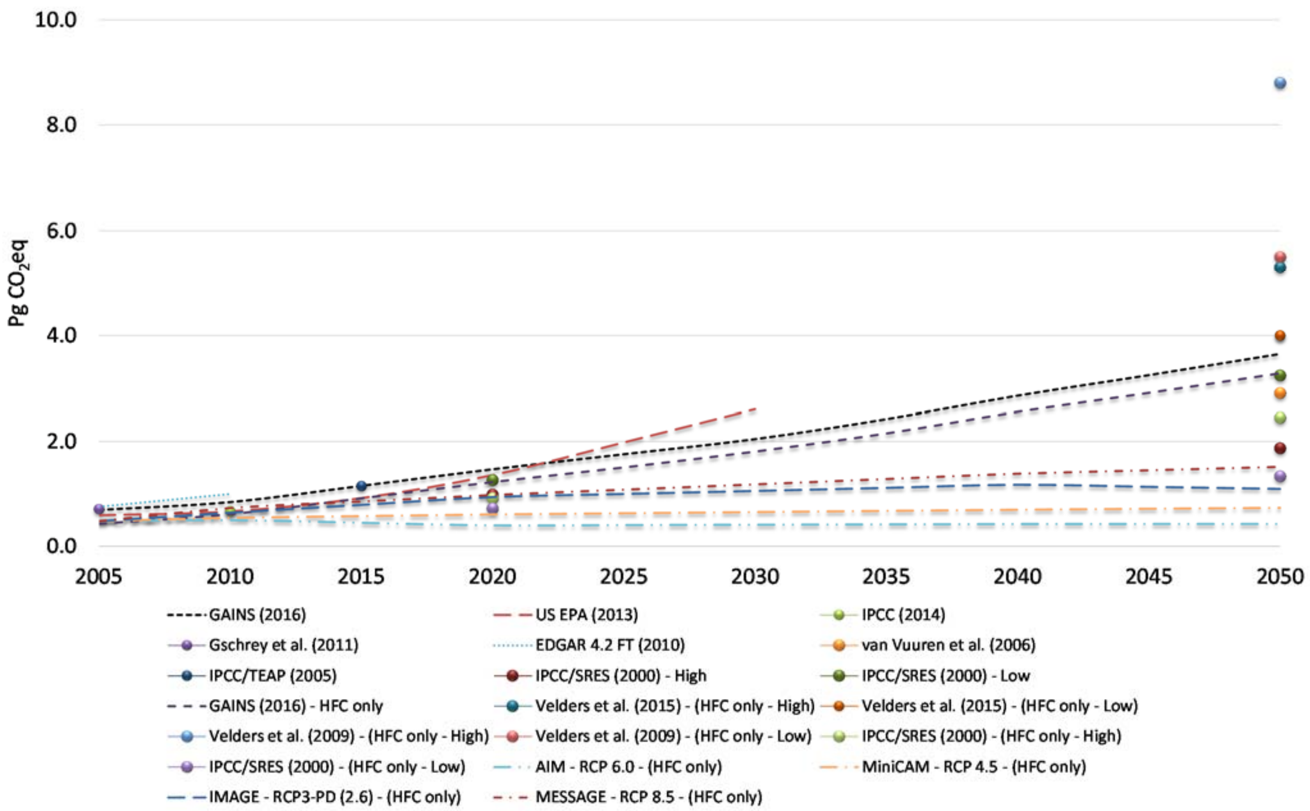


Figure ~~9~~10: Comparison of GAINS ~~emissions~~baseline scenario with other F-gas business-as-usual scenarios

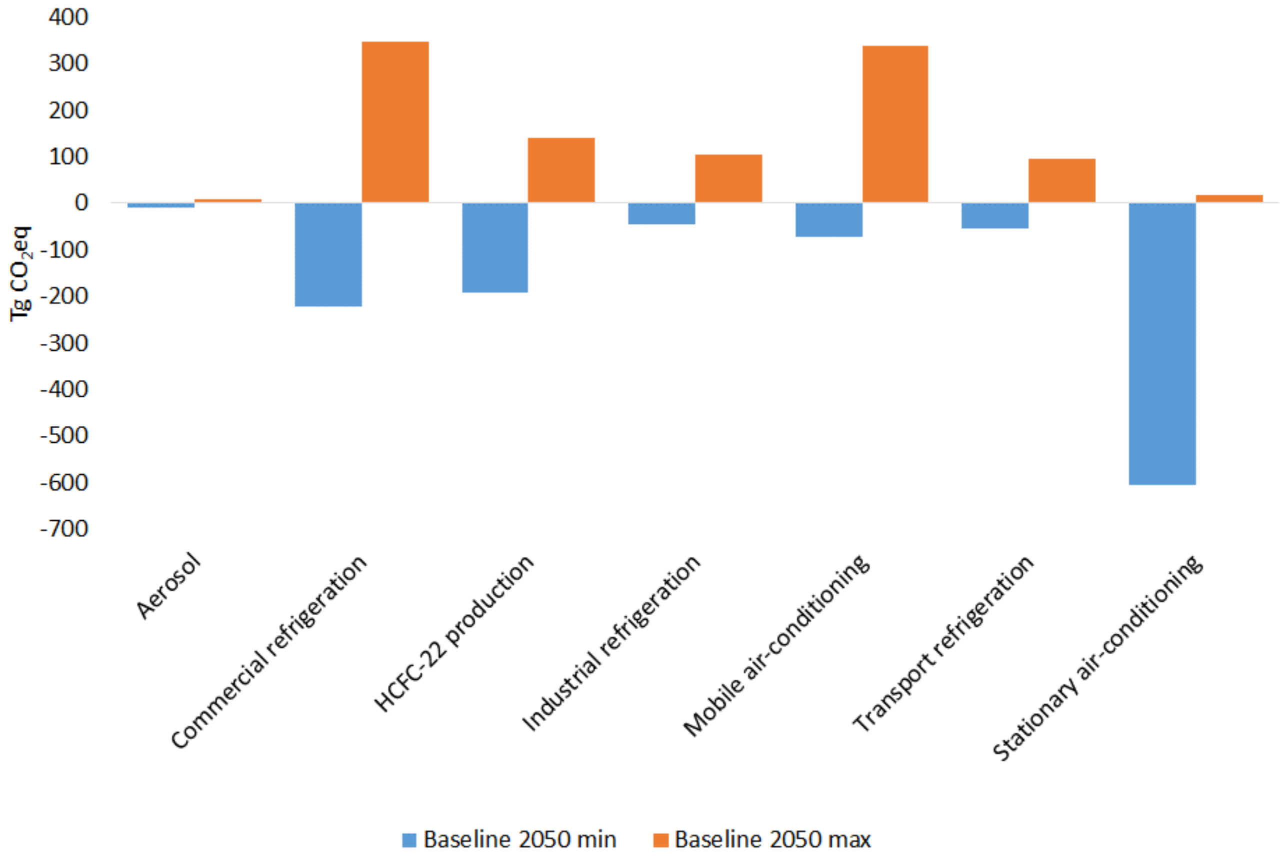


Figure ~~10~~11: Uncertainty ranges by sector for global F-gas emission estimates.

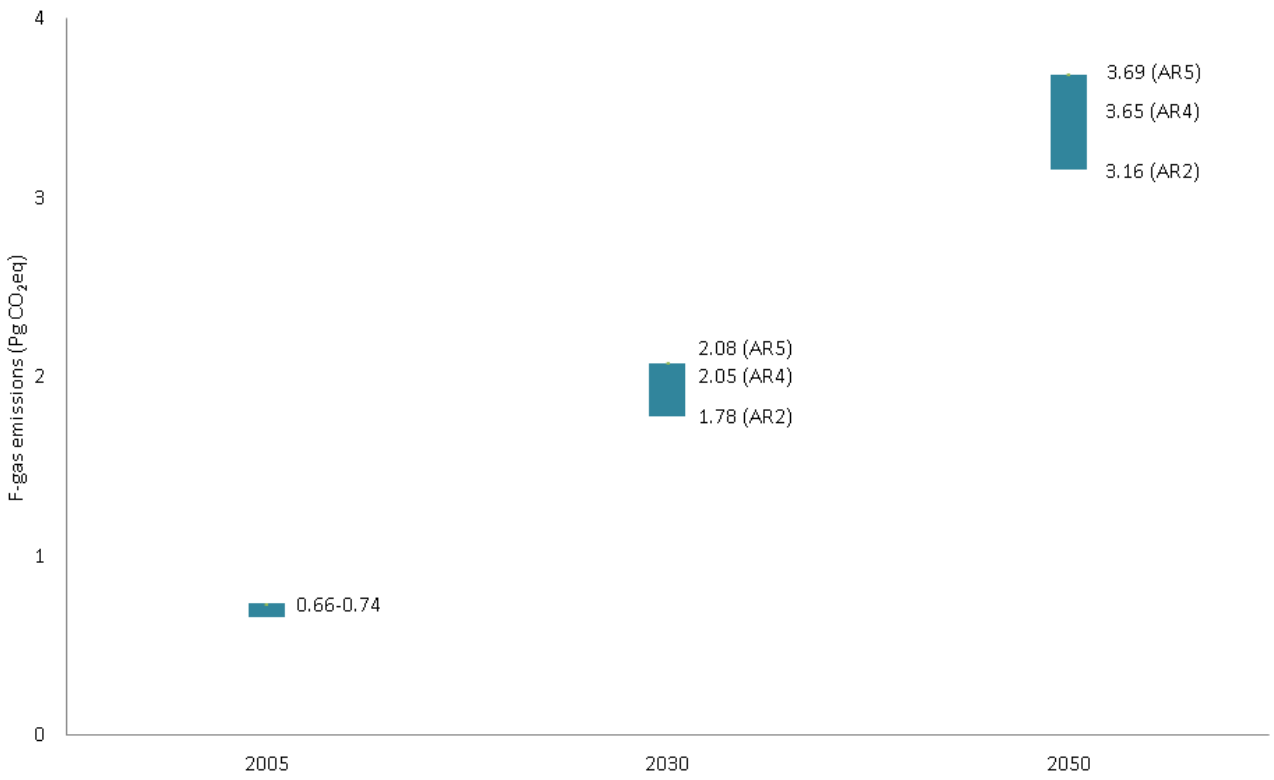


Figure ~~11~~12: Global F-gas emissions using different ~~GWP's~~GWPs.

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