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

[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**.

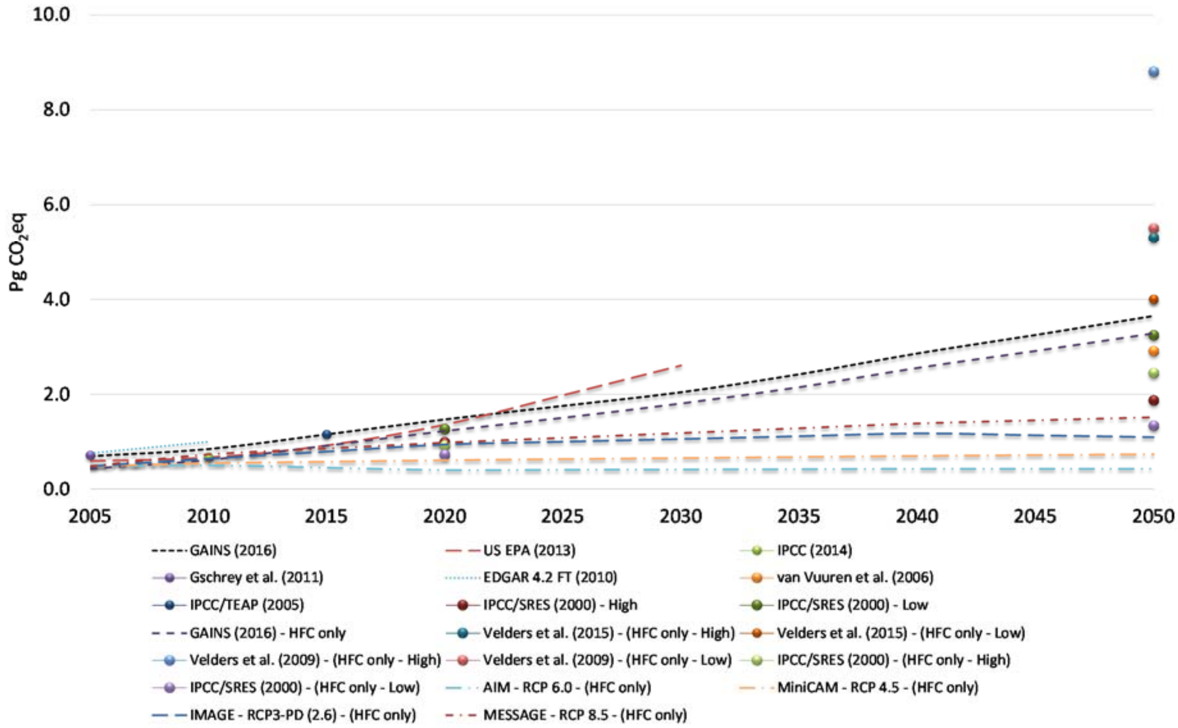

Figure 10: Comparison of GAINS baseline scenario with other F-gas business-as-usual scenarios

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.,

[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:

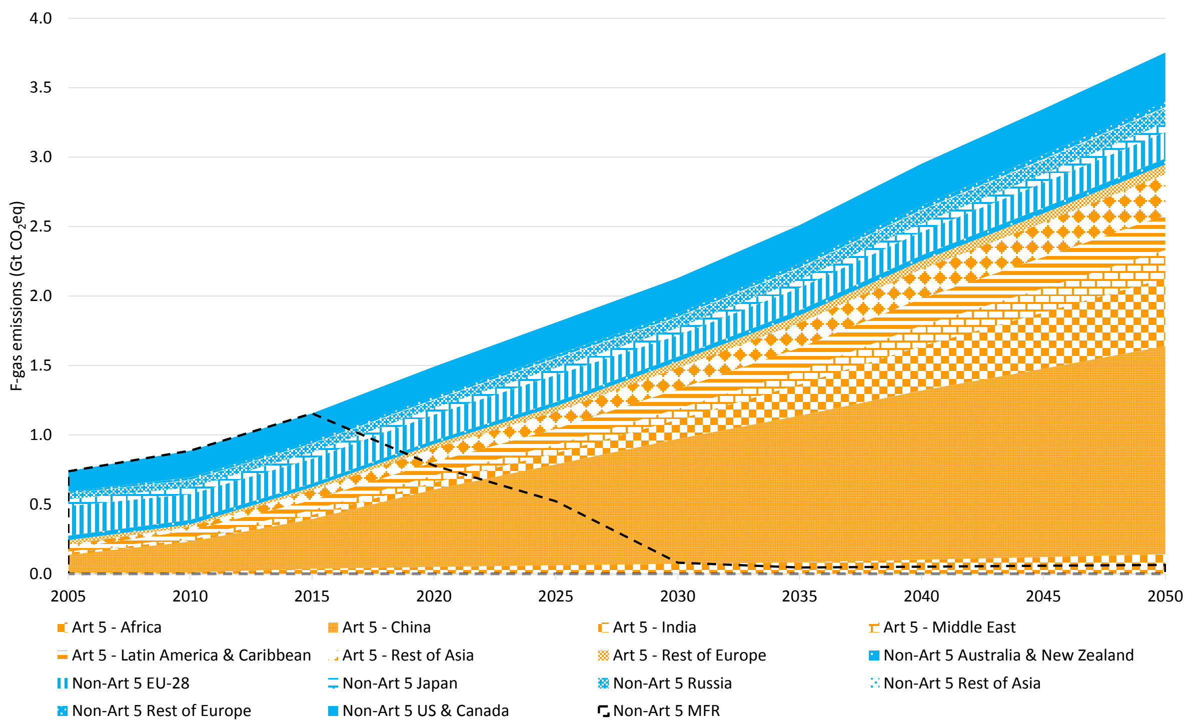

Figure 3: Baseline F-gas (HFCs, PFC and SF_6) emissions by major World regions (Article 5 in orange color and non-Article 5 countries in blue color).

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.

The reviewer seems to want to give the impression that the paper has many short-comings but without making an effort to explain what these short-comings are (except for the few listed below). We can of course only respond to short-comings that the reviewer actually lists and not address sweeping insinuations that are not explicitly stated 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.

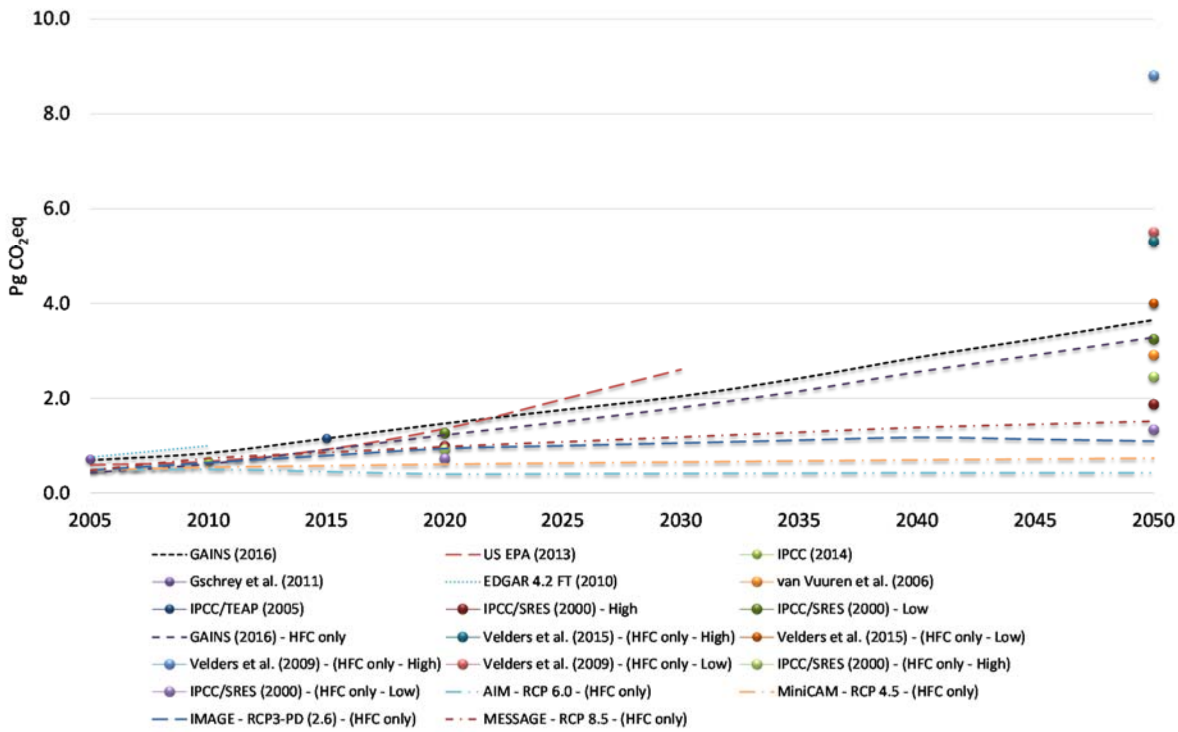

Figure 10: Comparison of GAINS baseline scenario with other F-gas business-as-usual scenarios

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_2eq/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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