Interactive comment on "Global emissions of fluorinated greenhouse gases 2005–2050 with abatement potentials and costs" *by* Pallav Purohit and Lena Höglund-Isaksson

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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 SF6, 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 SF6), 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 opportuni-

ties. We will also make sure to only consider HFCs, PFCs and SF6 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 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 SF6. Where PFC-SF6 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-SF6 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, SF6 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., 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.

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.), CO2, HFO-1234yf, NH3) 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."

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/acp-2016-727/acp-2016-727-AC2-supplement.pdf
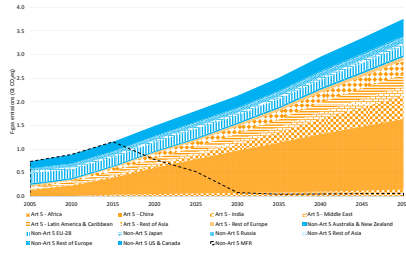
Figure 3: Baseline F-gas (HFCs, PFC and SF₆) emissions by major World regions (Article 5 in orange color and non-Article 5 countries in blue color).

Fig. 1.