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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Electricity savings and greenhouse gas emission reductions from global phase-down of hydrofluorocarbons" *by* Pallav Purohit et al.

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Referee #2 (Anonymous)

This is a very nice paper and it is timely. The calculations use the well-established GAINS model and uses various assumptions, most of which are documented. The paper shows that the use of low-GWP substitutes (including non-fluorinated refrigerants) for the high-GWP HFCs along with efficiency gains in better equipment design would help reduce climate change. This occurs through the reduction in the lower greenhouse effect of the substitutes and lesser CO2 emission from lower electricity usage.

The main concern I have about this paper is: Is ACP the right venue for this paper that is mostly about economic analyses and non-atmospheric assumptions. I have debated this for a few days and came to the conclusion that it would not hurt atmospheric scientists to read this paper to understand factors that go into decision making and the level of knowledge about the atmosphere that is used in such decision making! It should be eye-opening to them. I will leave it up to the Editor to make this call on suitability. But I stand on the side of publishing it here!

I have a number of comments for the authors to consider, some are small, and some are more important. I list them below.

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 a detailed point by point replies to the questions. We would like to emphasize that a large amount of additional information on existing policies for phasing down HFC consumption, baseline and HFC phase-down schedule of Article-5 and non- Article-5 Parties and results by different party groups, has been included – for the paper size reasons - in the supplementary material (see the attachment).

Main comments:

1. Personally, I don't think that there should be policy recommendations. I would cast the same recommendations as options and the gains made from such options. Policy recommendations do not go too well in science papers!

Authors' Response: Comment appreciated. We have rephrased section 5 as "Conclusions" instead of "Conclusions and Policy Recommendations".

2. The future warming is not the same across the globe. There are major regional and latitudinal differences. Also, the mean temperature is not what determines the use of cooling. It is the changes in the high temperatures. Do you account for these factors in your analysis? If you do not, you should explicitly state it and point out the uncertainties

that you get from such an assumption.

Authors' Response: We agree with the reviewer that the warming varies between global regions. While warming has not been uniform across the planet, the upward trend in the globally averaged temperature shows that more areas are warming than cooling. The influence of warming on cooling demand is much higher in tropical and sub-tropical regions, but other factors such as humidity and building performance also play a role. Therefore, in this study, the extension in demand for cooling services has been generated in consistency with the growth in population and macroeconomic indicators and the expected future increase in national/regional cooling degree days (CDDs) as developed and provided by International Energy Agency (IEA), as discussed in Section 2.1. Implemented at a national/regional level in our analysis, the CDDs increase globally on average by nearly 15% between 2016 and 2050 and 20% between 2016 and 2100 in the SSP3 baseline scenario. We have added the following footnote to provide more clarity on our assumptions in the revised version of the manuscript (See: footnote (10), Section 2.1):

"Cooling degree days (CDD) are country/region specific and measure how much (in degrees), and for how long (in days), outside air temperature was higher than a specific base temperature. For the purposes of this study, CDDs are measured in °C, standardized to 18°C, and adopted at a country/regional level in consistency with IEA (2018)."

3. I actually agree with your choice of baseline. But you need to discuss at least briefly how much difference it will make going forward. We are already in 2020!

Authors' Response: In the baseline scenarios (SSP3, Cooling for All and SSP1), we have considered, regional (EU) and national policies/regulations for phasing down HFC emissions (See: Section S1 of the SI). As a result, in industrialized countries, particularly Europe, HFC emissions are in decline due to ambitious national and regional policies to regulate F-gas use. However, a large increase is expected from developing

countries (primarily Article 5 parties) primarily in response to increased demand for cooling services and the phase-out of ozone-depleting substances under the Montreal Protocol.

The amount of energy needed to meet demand for space cooling varies mainly according to the type and efficiency of the equipment used, how it is used and how often it is used, as well as the type and thermal efficiency of buildings. The energy consumption per unit of cooling output of cooling technologies currently on sale around the world varies massively. We have used country/region specific information on unit energy consumption as shown in Table S2 of the SI. For the electricity savings, we consider both the technical and energy efficiency improvement potential of stationary cooling technologies due to systems improvement and transition towards low-GWP refrigerants. In addition, we have used a range of future energy sector developments (Current Policies Scenario, New Policies Scenario, and Sustainable Development Scenario) to assess country/region specific implied emissions factors for GHG and air pollutants to get a clear sense of the range of directions in which today's energy sector policy ambitions could impact GHGs and air pollution emissions from electricity savings.

As a result, full compliance with the Kigali Amendment means avoiding 631 Pg CO2eq of greenhouse gas emissions between 2018 and 2100. As explained in the text (Section 4.3.2), about 58% of this cumulative reduction can be attributed to the substitution of HFCs with other low-GWP alternatives, while about 42% can be attributed to electricity savings that derive from the realization of the technical potential to improve energy efficiency in cooling equipment. Hence, significant additional reductions in global warming can be achieved if the Montreal Protocol Parties address energy efficiency improvements in cooling technology simultaneously with requirements to substitute the use of HFCs with low-GWP alternatives.

4. How sensitive are your calculations to the assumption the efficiency gains made from switching from CFCs/HCFCs to HFCs is translated to going from high-GWP HFCs to lower GWP substitutes?

Authors' Response: Comment appreciated. The efficiency gains calculated are from improvements in the equipment (heat exchangers, compressors, valves etc.) and thus mostly independent of the refrigerant(s) used. The switch to lower GWP substitute refrigerants usually entails an efficiency gain or loss on the order of ∼5% which we assume would roughly cancel out when aggregated across product categories. Unfortunately, since the final refrigerant alternatives that will eventually be deployed and their characteristics are still being researched, while our work is based on the refrigerants that are currently available, it is not possible to be more specific than this in the current version of the manuscript.

5. Is there an upper limit to the efficiency gains that can be achieved?

Authors' Response: Yes, this is usually dictated by constraints such as thermodynamics, cost, weight, space and installation constraints if the dominant type of technology continues to be vapor compression systems. Current Best Available Technology is still roughly between 30-70% of the thermodynamically ideal efficiency (varying by the other constraints mentioned), as mentioned in Table S2 of SI.

6. Does this efficiency gain take into the change in the thermodynamic efficiency loss due to higher temperatures (not the global mean, but the location dependent predicted high temperatures)? Can this efficiency be improved if particular attention is paid to this factor? It would be nice to see something discussed here.

Authors' Response: No, however, it is anticipated in the scenarios examined in the paper that any losses of efficiency due to changes in temperature in the future are likely to affect both the baseline and higher efficiency technology roughly equally since most refrigerants decline in efficiency at higher ambient temperatures and thus there is not much to gain in efficiency terms by paying further attention to this factor.

7. Can you make some comments about the gains made if renewables were used? Afterall, you are projecting to 2100!

Authors' Response: Yes, this dimension is taken into account by using implied emission factors from IEA's Current Policies Scenario (CPS) and Sustainable Development Scenario (SDS). We have explained the impacts of replacement of fossil fuel use with renewable energy in Section 2.2 (L264-266). The GAINS model contains a database on region-specific emission factors for a range of air pollutants and greenhouse gases from energy production and consumption. From this source, we take implied emission factors per GWh electricity consumed for CO2, CH4, SO2, NOx, PM2.5 and SLCPs (BC and OC) and in reflection of expected country- and year- specific fuel mixes used in power plants in the IEA-WEO 2017 Current Policies Scenario (CPS), New Policies Scenario (NPS) and Sustainable Development Scenario (SDS), respectively, in the timeframe to 2040 (see: Figure S2 of the SI).

Note that the SDS represents a low carbon scenario consistent with a 2 oC (i.e., 450 ppm) global warming target for this century, and with considerably lower air pollution due to a high degree of replacement of fossil fuel use with renewable energy (solar, wind, biomass, etc.). Detailed implied emission factors are available from IIASA's GAINS model only in the timeframe to 2040. The country-, sector-, and fuel- specific implied emission factors for air pollutants per GWh electricity consumed representative for year 2040 have therefore been kept constant over the entire period 2040 to 2100.

The estimated reductions in CO2 and CH4 emissions from electricity savings are accordingly lower when using implied emission factors derived for the IEA-WEO17 SDS energy sector scenarios than for the CPS, because of higher penetrations of clean fuels (gas, renewables etc.) and uptake of energy efficiency measures in the power sector.

Specifics comments:

8. Not all HFCs are very potent greenhouse gases. You need to qualify your statements.

Authors' Response: As suggested, we have rephrased the sentences: (L12-13) –

“However, many HFCs are potent greenhouse gases. . . . . .” (L32-33) – “Many HFCs are potent greenhouse gases. . . . . .”

9. Your quoted GWP is for a mix of HFCs. You need to state this. Also, I think you are using 100-year GWPs, which are not necessarily appropriate since most HFCs have much shorter lifetimes and hence their shorter horizon GWPs are larger. How does that affect the near-term gains/disbenefits?

Authors’ Response: Comment appreciated. As already indicated in Section 2.1, L100-101, Blends of HFCs have been decomposed and attributed to respective HFC species. For e.g., HFC-410A (R-410A) a zeotropic mixture (a mixture of liquids that boils at a constant temperature, at a given pressure, without change of composition) of 50% HFC-32 and 50% HFC-125, HFC-407C (R-407C) a zeotropic mixture of 23% HFC-32, 25% HFC-125, and 52% HFC-134a. We agree that the lifetime of most of the HFCs is lower than 100 years except HFC-23 and HFC-236fa, GWP100 is lower than GWP20 (IPCC, 2013).

In the revised version of the manuscript, we have added the following paragraph on why we have chosen to use GWP100 (See: L105-114, Section 2.1): “In this study, we have chosen to follow the convention of the policy community to use IPCC global warming potentials over 100 years (GWP100) without climate-carbon feedback effects to convert the varying atmospheric lifetimes and warming potentials for different HFC species to CO2eq units (IPCC, 2013). This convention has been adopted in negotiations for several international climate agreements, e.g., the Kyoto Protocol, in the draft text of the Paris Agreement (UNFCCC, 2018), the standardized Life Cycle Assessment (LCA)/carbon-foot printing approaches (ISO, 2006) and in media and among the general public for assessing the relative climate impacts of given products or activities (Lynch et al., 2020). Despite there being good reasons for questioning this convention, in particular when analysing the impact of short-lived climate forcers (Cain et al., 2019), we find it well-motivated to apply the standard GWP100 metric here as it facilitates the discussion of results in the policy context. A broader assessment of implications of

results on global warming in the short- and long run could be an interesting topic for future research but is considered out of scope for this paper.”

There have been proposals for the UNFCCC to adopt a dual-term greenhouse gas accounting standard: 20-year GWPs alongside the presently accepted 100-year GWPs. It is argued that the advantage of such a change would be to more rapidly reduce short term warming and buy time for CO2 reductions. However, these changes could be counterproductive, and the benefits are overstated. The balance of near-term cooling followed by long-term warming would be even worse for 20-year GWPs, because this would “allow” dodging even more CO2 reductions for every unit amount of reduced short-lived greenhouse gas.

10. Somewhere in your model you have a specific fuel mix used to generate electricity. It would be useful to explicitly state those.

Authors’ Response: The GAINS model contains a database on country/region-specific emission factors (specific for 174 countries/regions as used in this study) for a range of air pollutants and greenhouse gases from energy production and consumption. From this source, we take implied emission factors per GWh electricity consumed for each pollutant and in reflection of expected country- and year- specific fuel mixes used in power plants in the IEA-WEO 2017 Current Policies Scenario (CPS), New Policies Scenario (NPS) and Sustainable Development Scenario (SDS), respectively, in the timeframe to 2040 (see: Figure S2 of the SI). Note that the SDS represents a low carbon scenario consistent with a 2 oC (i.e., 450 ppm) global warming target for this century, and with considerably lower air pollution due to a high degree of replacement of fossil fuel use with renewable energy. We have elaborated specific fuel mix used to generate electricity in Section 2.2 (L256-266).

11. I am impressed with your citation list! You are very comprehensive!

Authors’ Response: Thanks for encouraging words.

12. Have you considered that aerosols offset GHG of CO2? This happens only up to a point and then it does not. This influence can have major influences in the future (See Murphy and Ravishankara, PNAS, 2018).

Authors' Response: Comment appreciated. However, in this study, we have not considered the offsetting effects of the greenhouse gas and aerosol emissions as the primary focus of this study is to assess co-benefits in the form of electricity savings and associated reductions in greenhouse gas and air pollutant emissions due to the global phase-down of hydrofluorocarbons under the Kigali Amendment to the Montreal Protocol.

13. I am sorry to say that your figures are not easy to read, especially if somebody is partially colorblind. The lines are impossible to see, the axes are rather poorly formatted and too numerous to see. I assume (hope) that you will improve all your figures.

Authors' Response: We apologize for the inconvenience. As suggested, we have improved the font size and split Figure 3 in two parts – Marginal abatement cost curves (MACCs) starting from a pre-Kigali SSP3 baseline consistent with the IEA-WEO17 New Policies scenario and reducing HFC emissions by KA party groups under a) technical energy efficiency improvements in the revised manuscript; and b) economic energy efficiency improvements in the supplementary section (Figure S4).

In the revised version of the manuscript, Figure 4 on "Technical and economic electricity saving (TWh) potentials in HFC reduction scenarios (KA and MTFR) relative pre-KA baselines (SSP3 and Cooling for All)" is deleted as suggested by the reviewer#1. In addition, we have improved the font size and readability of Figure 6 (now Figure 5) in the revised version of the manuscript.

Finally, we have improved the font size and split Figure 8 in two parts – a) Impacts on air pollutant emissions due to electricity savings are presented in the revised manuscript whereas the b) Impacts on BC/OC emissions due to electricity savings are presented in the supplementary section (Figure S8). âĂČ

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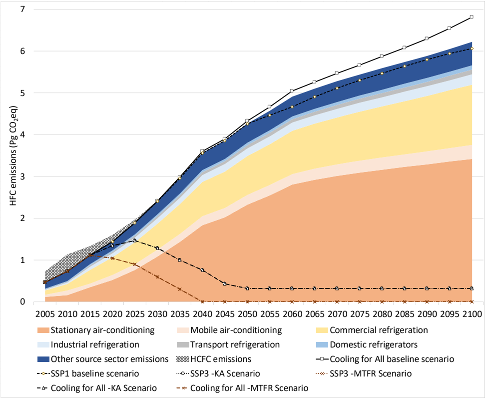

Figure 1: Pre-Kigali SSP3 baseline HFC emissions (with baseline SSP1 and *Cooling for All* shown for comparison) and respective alternative scenarios (Kigali Amendment -KA and Maximum Technically Feasible Reduction -MTFR). Note that *Cooling for All* -KA and *Cooling for All* -MTFR scenarios are not visible due to the small differences in mitigation scenarios to SSP3 -KA and SSP3 -MTFR.

Fig. 1.

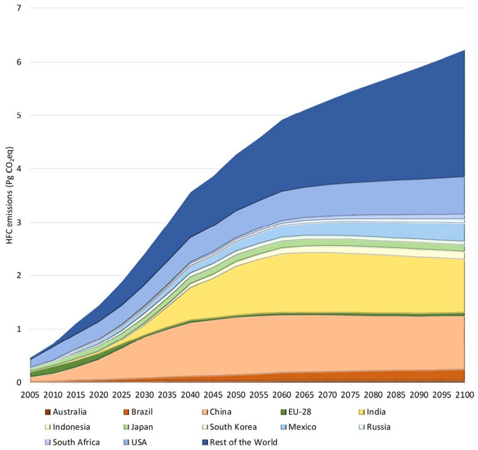

Figure 2: Pre-Kigali SSP3 baseline HFC emissions by regions

Fig. 2.

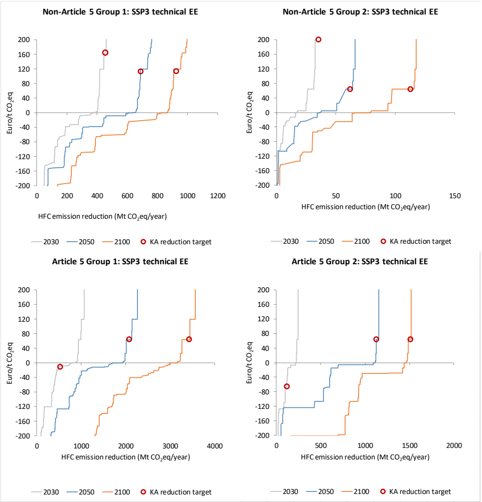

Figure 3: Marginal abatement cost curves (MACCs) starting from a pre-Kigali SSP3 baseline consistent with the IEA-WEO17 New Policies scenario and reducing HFC emissions by Kigali Amendment (KA) party groups under technical energy efficiency improvements and indicating the KA HFC reduction targets in 2030, 2050 and 2100.

Fig. 3.

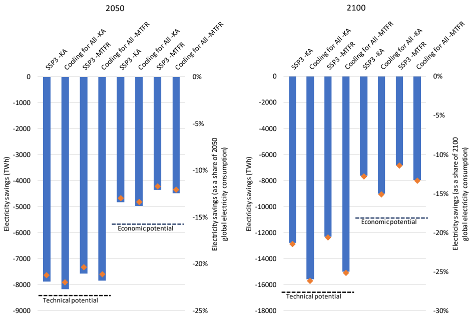

Figure 4: Annual electricity saving potentials when moving from pre-Kigali baselines (SSP3 and *Cooling for All*) to HFC reduction scenarios (Kigali Amendment -KA and Maximum Technically Feasible Reduction -MTFR), in absolute TWh (blue bars) and as a fraction of expected future global electricity consumption in the AIM/CGE SSP3 baseline scenario (Riahi et al., 2017) (orange dots).

Fig. 4.

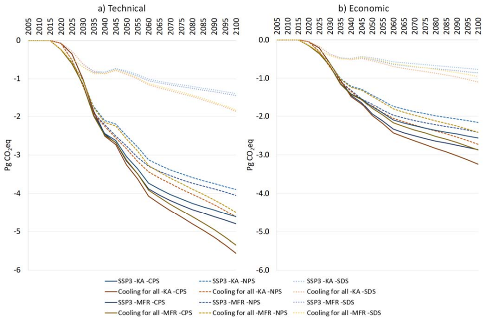

Figure 5: Annual greenhouse gas emission reductions from electricity savings in the Kigali Amendment (KA) and Maximum Technically Feasible Reduction (MTFR) scenarios relative the pre-Kigali baseline scenarios (SSP3 and *Cooling for All*). Results for technical energy efficiency improvements are shown in Panel a) and for economic energy efficiency improvements in Panel b).

Fig. 5.

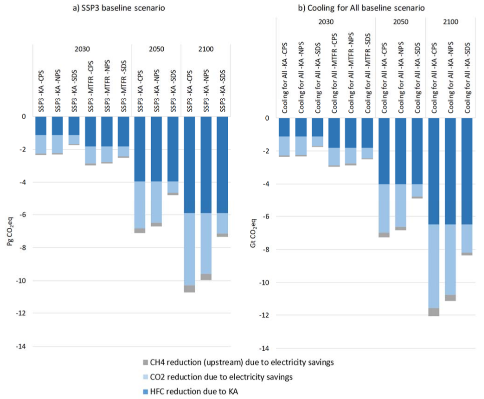

Figure 6: Greenhouse gas mitigation (in Pg CO$_2$eq) due to enhanced energy efficiency benefits under Kigali amendment (KA) in the alternative scenarios with respect to the a) SSP3 baseline scenario and b) *Cooling for All* baseline scenario. In 2050 and 2100 differences between KA and Maximum Technically Feasible Reduction (MTFR) scenarios are negligible.

Fig. 6.

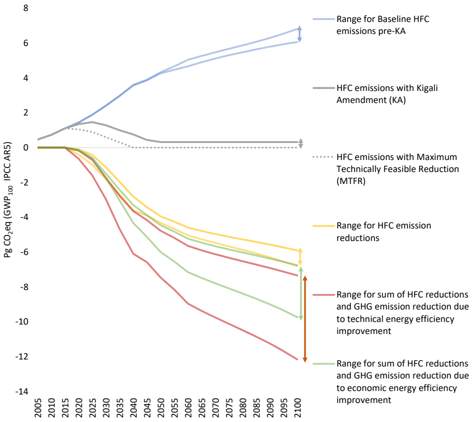

Figure 7: Full range of HFC emissions and mitigation potential under baselines and Kigali Amendment (KA) and Maximum Technically Feasible Reduction (MTFR) scenarios along with HFC and other greenhouse gas mitigation under technical and economic energy efficiency improvement scenarios analysed in this study.

Fig. 7.

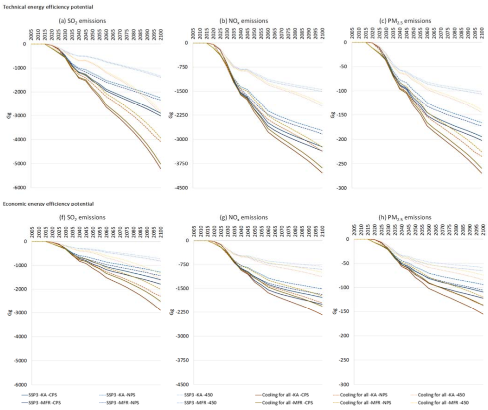

Figure 8: Impacts on air pollutant emissions due to electricity savings associated with alternative HFC phase-down pathways.

Fig. 8.

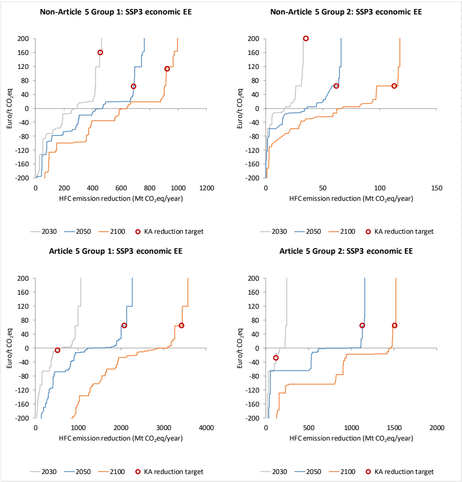

Figure S4: Marginal abatement cost curves (MACCs) starting from a pre-Kigali SSP3 baseline consistent with the IEA-WEO17 New Policies scenario and reducing HFC emissions by Kigali Amendment (KA) party groups under economic energy efficiency improvements and indicating the KA HFC reduction targets in 2030, 2050 and 2100.

Fig. 9.

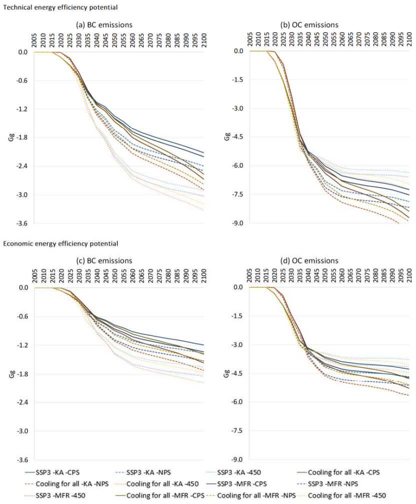

Figure S8: Impacts on BC/OC emissions due to electricity savings associated with alternative HFC phase-down pathways.

Fig. 10.