Atmos. Chem. Phys. Discuss.,
https://doi.org/10.5194/acp-2020-193-AC1, 2020

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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Received and published: 17 July 2020

Referee 1 (Anonymous)

The authors discuss the emissions of HFCs under several scenarios, with and without the controls of the Kigali Amendment. The novel aspect is that they not only consider the direct climate effects, but also the indirect effects, through changes in the energy use and related air quality aspects. The paper is scientifically sound, and the results are interesting and policy relevant. The presentation of the results, though, needs to be improved. There are too many figures with too many panels and lines, which makes it hard to get the main message. The abstract also needs more focus on what is new and

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not presenting results that have been shown by others also before. I think the paper is acceptable for publication in ACP, after the presentation has been improved.

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. We would like to emphasize that a large amount of additional information on existing policies for phasing down hydrofluorocarbon (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 paper size reasons in the supplementary material (see the attachment). In the revised version of the manuscript, we have improved the abstract, figures and overall presentation of the results as suggested by the reviewer.

Main comments:

1. The abstract needs more focus and needs to be shortened. Focus the abstract on what is new (energy savings and air quality aspect), not on results similar to those that have been presented in papers already before. The results on avoided HFC emissions are presented in the conclusions (section 5) and don't need a prominent place in the abstract.

Authors' Response: As suggested, we have shortened the abstract (from 355 words to 266 words) in the revised version of the manuscript primarily focusing on co-benefits (electricity savings and reduction in air pollutants and greenhouse gas emissions) of the HFC phase-down under Kigali amendment (KA) to the Montreal Protocol.

2. The paper contains too many figures; they distract the reader from the main message. Most figures also contain a lot of lines which makes them hard to read and to get the main message out of them. Figure 3: two panels as an example is enough, the rest can be put in the SI. Figure 4 is not needed, since Figure 5 shows the same information in a much clearer way. Figure 6: is this figure needed, if yes, reduce the number of lines. Figure 7 is good and clear. Figure 8 is not readable, too many panels

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and too many lines. Replace with one clear figure and move the rest to the SI. Some figures also need larger legend.

Authors' Response: 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.

As suggested, we have improved the font size and readability of Figure 6 in the revised version of the manuscript.

Once again, 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).

3. The paper contains a lot of acronyms which makes it not easy to read. The authors should try to avoid acronyms when they are not needed and mostly spell them out in tables and figures, or at least explain the acronyms in all the captions of figures and tables.

Authors' Response: As per the reviewer's comments, we have reduced acronyms to the extent possible in the revised version of the manuscript. In addition, we have spelled out most of the acronyms in all figures and tables of the paper.

Specifics comments:

4. L10-24: These lines in the abstract could be shortened significantly. Only at L24

new information is presented.

Authors' Response: As suggested, we have shortened the abstract (from 355 words to 266 words) in the revised version of the manuscript.

5. In L24-29 I would also mention the effects of the economic vs technical mitigation potential. This is a very important and policy-relevant result.

Authors' Response: Corrected in the revised version of the manuscript (See: L19-25). We have rephrased the text and highlighted the effects of the economic vs technical mitigation potential:

"If technical energy efficiency improvements are fully implemented, the resulting electricity savings could exceed 20

In addition, Table 5 of the revised manuscript also presents cumulative reductions in GHG emissions 2018-2100 due to electricity-savings induced by HFC phase-down when assuming economic energy efficiency improvement potentials, by Kigali Amendment party groups.

6. L11-12: HFCs are not the primary substitute for ODSs under the Montreal Protocol. In many applications, ODSs have been replaced by not-in-kind substitutes, such as in cleaning and foam blowing, while hydrocarbons have been used in large quantities in small refrigeration units. I would write "They have been used in large quantities as: :"

Authors' Response: Comment appreciated. As suggested, we made the following change in the revised version of the manuscript (See: L11-12):

"They have been used in large quantities as the primary substitutes for ozone-depleting substances regulated under the Montreal Protocol (MP)."

7. L33: ": : :and emissive use'. Maybe better to write ": : :and use as refrigerant"

Authors' Response: Comment appreciated. As suggested, we made following change in the revised version of the manuscript (See: L28-29).

"As well, HFC-23 is generated as a by-product of chlorodifluoromethane (HCFC-22) production used in refrigerants and as a chemical feedstock for manufacturing synthetic polymers."

8. L40: Spell out HFO when it is first mentioned.

Authors' Response: Corrected, . . . hydrofluoroolefins or HFOs in short. . . in the revised version of the manuscript (See: L36).

9. L45: Please specify the composition of the party groups in the main text (or footnote or caption). Now it is only specified in the SI. Also, the word 'group' is confusing, and Group I and group II even more so. In the Protocol, groups are defined in Annexes as a set of chemical species. A suggestion: use A5 group A, B, nonA5 group A, B.

Authors' Response: Article 5 and non-Article 5 parties are defined within the Montreal Protocol based on their annual calculated level of consumption of any controlled substance per capita. Those that exceed this level of annual calculated consumption are classified as non-Article 5 and those that do not exceed it as Article 5 parties. For the groups, we have used the classification from UNEP Ozon Action (See: http://www.unep.fr/ozonaction/information/mmcfiles/7880-e-Kigali$_FS05_Baselines_Timetable.pdf).WesimplywriteGroup1andGroup2intherevisedversionofthemanuscriptinsteadofGroup-IandGroup-II.Assugge$

"The Montreal Protocol Parties are split into four Kigali Amendment groups: a) Non-Article 5, earlier start - Most non-Article 5 countries; b) Non-A5, later start - Russia, Belarus, Kazakhstan, Tajikistan, Uzbekistan; c) Article 5, Group 1 - Most Article 5 countries; and d) Article 5, Group 2 - Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia and UAE."

10. L115-119: SSP3 is selected as primary scenario and SSP1 as a sensitivity case. I find the logic not very convincing. The largest differences between in all SSP scenario (1 to 5) occur after 2040 and more even later, so that fact that SSP3 is closest to the IEA scenario up to 2040 is not a very strong argument. So if you select SSP3 as

primary scenario than use the highest and lowest of the SSP scenarios (I guess 4 and 5 in your case) for sensitivity. They show the range of results, especially for the second half of this century. Clearly, under the KA they all collapse on to one curve.

Authors' Response: We agree with the reviewer's comment that under KA all SSP scenarios will collapse on to one curve. We have now tried to better motivate our choice of SSP3 as main baseline scenario by adding the following footnote (11) in L128 (Section 2.1):

"With the exception of SSP5 and as shown in Figure S1 of the SI, SSP1 and SSP3 represent roughly the full range of future population and GDP developments in the SSPs. SSP5 is not considered as a baseline in this study, since the dimension of a continued fossil-fuel intensive future vs a decarbonized future is already integrated in the analysis through the range of country-specific implied emission factors from the CPS vs the SDS scenarios of the IEA-WEO2017. In the period beyond 2040, the country- sector- and fuel specific emission factors derived from these scenarios for the year 2040 are kept constant."

11. L180: What do you mean with 'HFC removal efficiency'? To me it could mean, replacing HFCs with other substances or NIK technologies, but also HFC capture and destruction.

Authors' Response: We agree with the reviewer's comment that the way we have used this expression was confusing. We have replaced this expression everywhere with 'efficiency in reducing the climate impact of cooling when replacing HFC use' to make it clearer what we mean (See: L188, Section 2.2).

12. L181: Again, what is 'removal of HFCs'? I also don't understand the rest of the sentence. 'removal of HFCs is close to complete: : :not affect conclusions regarding the HFC phase-down'. If removal is complete does that mean the phase down is complete? Please clarify this sentence.

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Authors' Response: We have tried to rewrite these sentences to hopefully be clearer about what we mean (See: L187-194, Section 2.2):

"Note that for given technology options, potential effects of future technological development on costs and the efficiency in reducing the climate impact of cooling when replacing HFCs, have not been considered here. It would also not have a significant impact on conclusions of this study, since the use of HFCs in cooling can be completely replaced by existing alternative low-GWP measures, and cost are not assessed at the absolute level but for the sole purpose of using MACCs to determine the order of technology uptake. Technological development could also mean even larger potentials for energy efficiency improvements than those considered here as technical and economic potentials. Not considering the possibility of such effects here may be considered a conservative assumption, as it could mean there are potentials for even larger future electricity savings."

13. L218-219: 'no information : : : was provided : : :' This is an odd argument. Improvements in MAC are clearly taking place, although maybe not directly related to energy efficiency. How it will affect CO2 emissions and air quality is a completely different study and I can understand that that is the reason it is not taken into account here. I would rephrase the sentence.

Authors' Response: Comment appreciated. As suggested, we have rephrased the sentence in the revised version of the manuscript (L228-230, Section 2.2) as follows:

"Note that energy efficiency improvements take place also when HFCs are replaced in mobile air conditioners (MAC) (Blumberg et al., 2019). These are however not accounted for here as the drivers for associated emission changes are very different from those in stationary sources and more complex to estimate."

14. L232-233: 'The electricity generation units: : :'. Please specify what units will be used first. I can imagine that this is different in different countries. What did you assume?

Authors' Response: To be clearer about what we mean, we have replaced "units" with "plants" (See: L245-248, Section 2.2). The sentence now reads "The electricity generation plants (e. g. coal, oil and gas fired power plants) that respond to this increased demand are major contributors to SO2 and NOx emissions, both of which have direct impacts on public health, and contribute to the formation of secondary pollutants including ozone and fine particulate matter (PM2.5)."

The assumptions for deriving country-, sector- and fuel- specific implied emission factors from the GAINS model are explained further down in the text (Section 2.2).

15. L277: What is meant with ': : :at least to a limited extent.' This weakens the rest of the sentence considerably.

Authors' Response: To avoid confusion, we have deleted the text ". . . . .at least to a limited extent" from this sentence.

16. L289-294: I agree with this paragraph, but it would be good to have a reference for it. Authors' Response: As suggested, we have added the following references in this paragraph (See: L301, Section 3): 1. Beshr, M., Aute, V., Sharma, V., Abdelaziz, O., Fricke, B. and Radermacher, R.: A comparative study on the environmental impact of supermarket refrigeration systems using low GWP refrigerants, Int. J. Refrigeration, 56, 154-164, https://doi.org/10.1016/j.ijrefrig.2015.03.025, 2015. 2. McLinden, M.O., Brown, J.S., Brignoli, R., Kazakov, A.F. and Domanski, P.A.: Limited options for low-global warming potential refrigerants, Nature Communications, 8, https://doi.org/10.1038/ncomms14476, 14476, 2017. 3. Heredia-Aricapa, Y., Belman-Flores, J.M., Mota-Babiloni, A., Serrano-Arellano, J. and García-Pabón, J.J.: Overview of low GWP mixtures for the replacement of HFC refrigerants: R134a, R404A and R410A, Int. J. Refrigeration, 111, 13-123, https://doi.org/10.1016/j.ijrefrig.2019.11.012, 2020. 4. UNEP: Lower-GWP Alternatives in Commercial and Transport Refrigeration: An expanded compilation of propane, CO2, ammonia and HFO case studies, United Nations Environment Programme (UNEP), Paris, 2016a.

17. L289: Be careful with the term low-GWP alternatives (see my comment with Table 2)

Authors' Response: Thanks for pointing out the error. We have changed the title of Table 2 to "Sector specific alternative options for high-GWP hydrofluorocarbons considered in the GAINS model".

18. L345-347: You have to mention somewhere that in, e.g., the EU, Japan, Australia HFC regulations are already in place and preceded the time the KA came into force. The situation in the US is complicated.

Authors' Response: Comment appreciated. In the supplementary information (SI) section, we have provided a separate section S1 on "Current legislation on HFC control considered in the Baselines" – highlighting HFC control or phase-down policies at regional and national level in Article 5 and non-Article 5 countries.

As suggested, we have added the following text at the end of Section 4.1 (L356-358) of the revised manuscript:

"In non-Article 5 countries (mainly developed countries), national and regional (e.g. EU) regulations have been implemented to limit the use of high-GWP HFCs through limiting imports, production and exports prior to the Kigali amendment entering into force. More specific information about these regulations is available in Section S1 of the SI."

19. L348: Very useful paragraph. The corresponding figure (3) needs to be simplified (see below). Have the national/regional regulations that are already in place been taken into account here? In the EU for example the phasedown of HFCs is already well underway.

Authors' Response: 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 of the SI).

We have considered the national/regional regulations (e.g. EU F-gas regulations) in the baseline scenarios. More specific information about these regulations is available in Section S1 of the Supplementary Information on - Current legislation on HFC control considered in the Baselines. We have referred this section here (L368, Section 4.2).

20. L436-440: There are many acronyms in section 4.3.3. Please spell out CPS, NPS, SDS. This makes it easier to read.

Authors' Response: We have explained all three scenarios (current policies scenario – CPS; new policies scenario – NPS; and sustainable development scenario- SDS) in Section 2.2 in the revised version, and thereafter refer to them consistently as "CPS, NPS, and SDS energy scenarios" in Section 4.3.3.

21. L783: Figure 3: Simplify this figure by moving panels to the SI. The message comes much better across with only two panels.

Authors' Response: 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).

22. L790: Figure 4 shows negative numbers for savings. I think this is confusing. Or 'savings' or negative/reduced electricity use. In also Figure 5 where positive savings are shown.

Authors' Response: We have replaced "savings", which indeed was incorrect if expressed in negative numbers, to "Potentials for changes in annual electricity consump-

tion".

23. L800: Same as in figure 4. Confusing to show negative emission reductions.

Authors' Response: Same here, reductions changed to "Changes in annual GHG emissions". Thanks for pointing this out.

24. L805: Same as figure 4 and 5 L810: Figure 8: Very unclear: too many panels and too small numbers. This figure has to be improved.

Authors' Response: As suggested, we have improved the font size and split Figure 8 in two parts: Impact on a) air pollutant emissions (see: Figure 8 of the revised manuscript), and b) BC/OC emissions (Figure S8 of the supplementary section) due to electricity savings associated with alternative HFC phase-down paths.

25. Table 1: I think the table can be simplified, since almost all scenarios have an 'X'.

Authors' Response: In the revised version, we have used "âIJŞ" for the scenarios analyzed and "X" for the scenario not considered (see: Table 1) in this study.

26. L815: Table 2: HFC-32 is mentioned here as a low GWP alternative. This is confusing. There has been a lot of discussions in among parties to the Montreal Protocol on the term low-GWP. A value of 150 is sometimes considered 'low' because it is a value used in the EU regulation. HFC-32 is not considered a low GWP alternative. It is used as an alternative with a 'lower' GWP than the compound it replaces. Please use the terms 'alternatives' and 'low-GWP' carefully.

Authors' Response: We appreciate the reviewers' comments. As suggested, we have changed the title of Table 2 as "Sector-specific alternative options for high-GWP hydrofluorocarbons considered in the GAINS model".

Please also note the supplement to this comment:
https://www.atmos-chem-phys-discuss.net/acp-2020-193/acp-2020-193-AC1-supplement.pdf

Interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2020-193, 2020.

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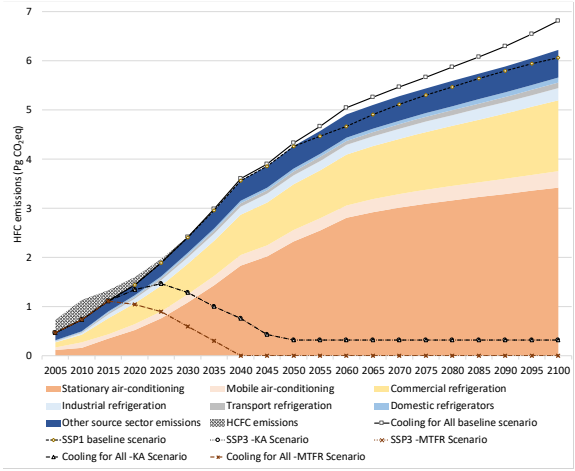

Figure 1: Pre-Kigali SSP3 baseline HFC emissions (with baseline SSP1 and *Cooling for All* shown for comparison) and respective alternative scenarios (Kigali Amendment -KA and Maximum Technically Feasible Reduction -MTFR). Note that *Cooling for All* -KA and *Cooling for All* -MTFR scenarios are not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

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Fig. 1.

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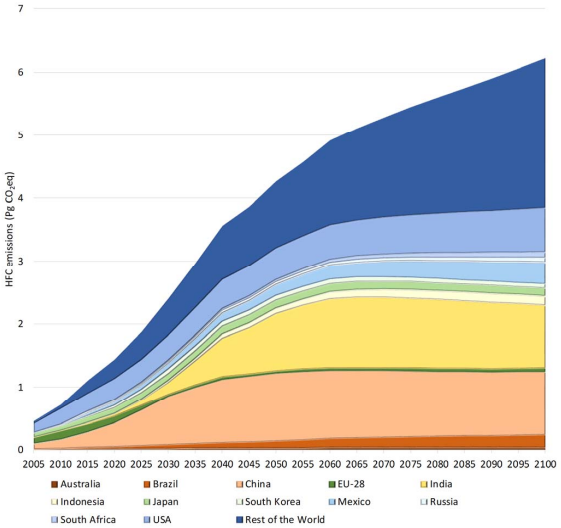

Figure 2: Pre-Kigali SSP3 baseline HFC emissions by regions

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Fig. 2.

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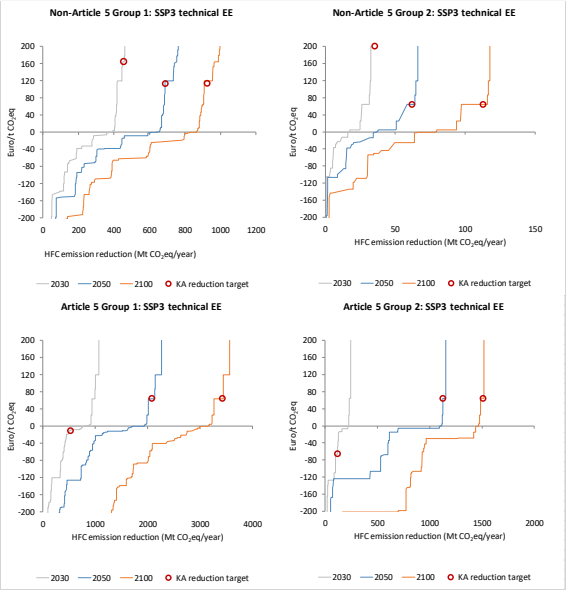

Figure 3: Marginal abatement cost curves (MACCs) starting from a pre-Kigali SSP3 baseline consistent with the IEA-WEO17 New Policies scenario and reducing HFC emissions by Kigali Amendment (KA) party groups under technical energy efficiency improvements and indicating the KA HFC reduction targets in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

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Fig. 3.

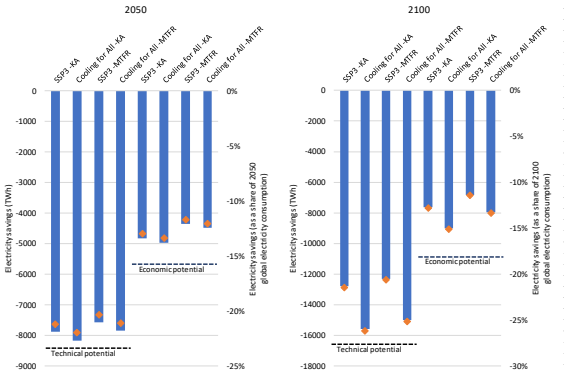

Figure 4: Annual electricity saving potentials when moving from pre-Kigali baselines (SSP3 and *Cooling for All*) to HFC reduction scenarios (Kigali Amendment -KA and Maximum Technically Feasible Reduction -MTFR), in absolute TWh (blue bars) and as a fraction of expected future global electricity consumption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

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Fig. 4.

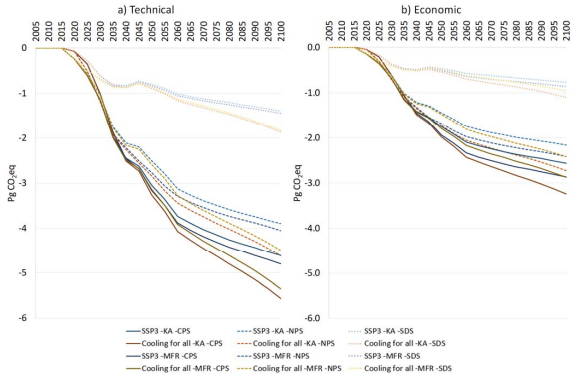

Figure 5: Annual greenhouse gas emission reductions from electricity savings in the Kigali Amendment (KA) and Maximum Technically Feasible Reduction (MTFR) scenarios relative the pre-Kigali baseline scenarios (SSP3 and *Cooling for All*). Results for technical energy efficiency improvements are shown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

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Fig. 5.

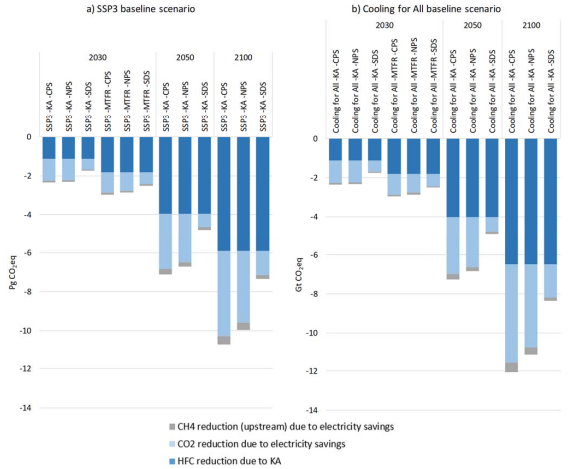

Figure 6: Greenhouse gas mitigation (in Pg CO_2eq) due to enhanced energy efficiency benefits under Kigali amendment (KA) in the alternative scenarios with respect to the a) SSP3 baseline scenario and b) *Cooling for All* baseline scenario. In 2050 and 2100 differences between KA and Maximum Technically Feasible Reduction (MTFR) scenarios are negligible.

Fig. 6.

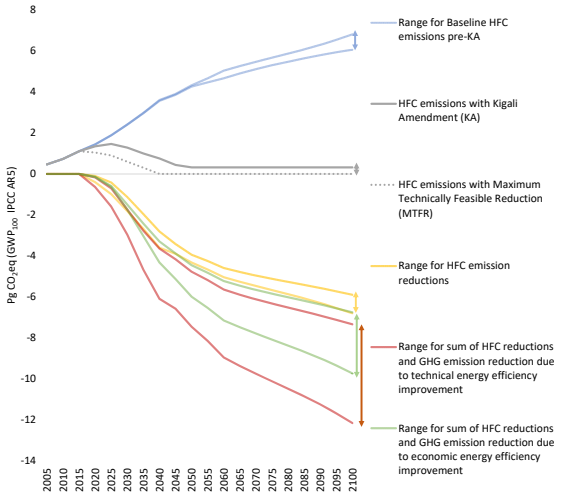

Figure 7: Full range of HFC emissions and mitigation potential under baselines and Kigali Amendment (KA) and Maximum Technically Feasible Reduction (MTFR) scenarios along with HFC and other greenhouse gas mitigation under technical and economic energy efficiency improvement scenarios analysed in this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

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Fig. 7.

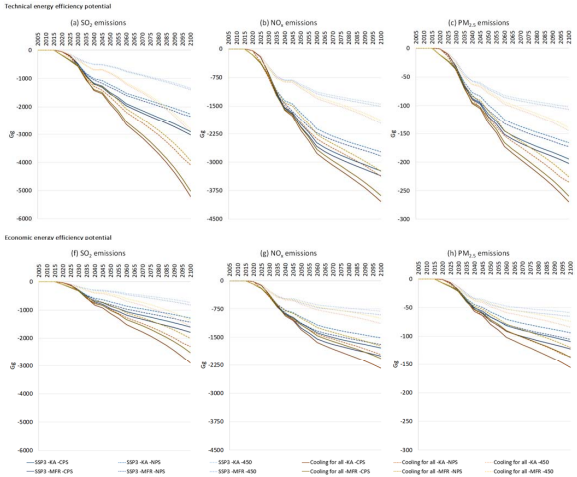

Figure 8: Impacts on air pollutant emissions due to electricity savings associated with alternative HFC phase-down pathways.

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Fig. 8.

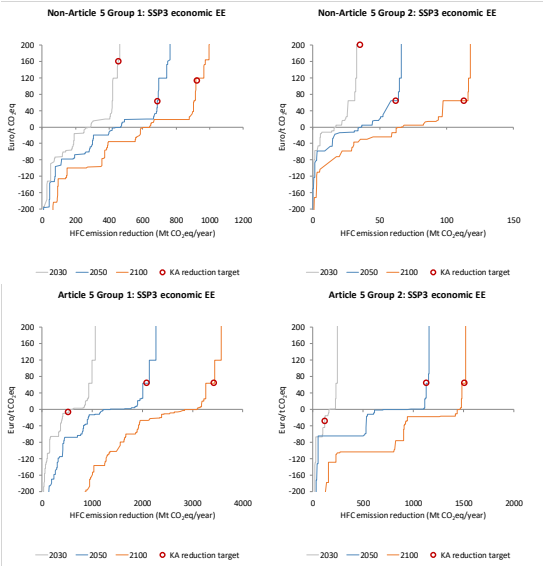

Figure S4: Marginal abatement cost curves (MACCs) starting from a pre-Kigali SSP3 baseline consistent with the IEA-WEO17 New Policies scenario and reducing HFC emissions by Kigali Amendment (KA) party groups under economic energy efficiency improvements and indicating the KA HFC reduction targets in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

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Fig. 9.

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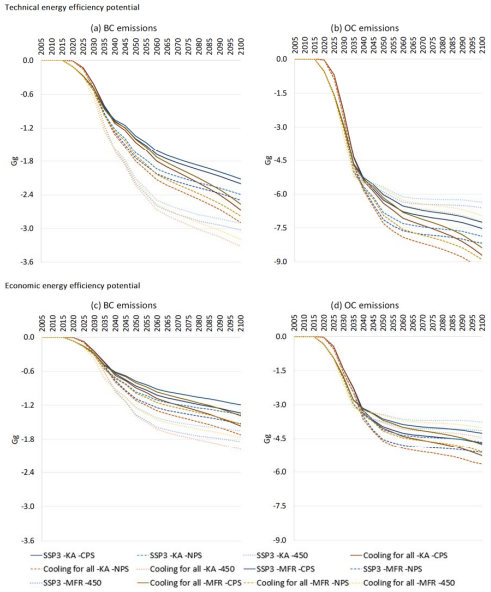

Figure S8: Impacts on BC/OC emissions due to electricity savings associated with alternative HFC phase-down pathways.

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Fig. 10.