Journal: Atmospheric Chemistry and Physics

Title: Electricity savings and greenhouse gas emission reductions from global phase-down of hydrofluorocarbons

MS No.: acp-2020-193

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 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. Referee comments are quoted in italics and authors' responses in blue. 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 274 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 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 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% of future global electricity consumption, while the corresponding figure for economic energy efficiency improvements would be 15%. Together with a HFC phase-down, this means preventing between 411 and 631 Pg CO_2 equivalent of GHG emissions between 2018 and 2100, thereby making a significant contribution towards keeping the global temperature rise below 2°C. Reduced electricity consumption also means lower air pollution emissions in the power sector, estimated at about 5-10% for SO_2, 8-16% for NO_x and 4-9% for $PM_{2.5}$ emissions compared with a pre-Kigali baseline."

   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.

   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 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)."

6. *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."

7. *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).

8. *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). We simply write Group 1 and Group 2 in the revised version of the manuscript instead of Group-I and Group-II. As suggested, we have added the following footnote (1) in L42 of the introductory section and referred Table S1 in the revised manuscript:

"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."

9. *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."

10. *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).

11. *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.*
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."

12. *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 CO_2 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."

13. *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 SO_2 and NO_x emissions, both of which have direct impacts on public health, and contribute to the formation of secondary pollutants including ozone and fine particulate matter ($PM_{2.5}$)."

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).

14. *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.

15. *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.

16. *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".

17. *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."

18. *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).

19. *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.

20. *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).

21. *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 consumption".

22. *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.

23. *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.

24. *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 "✓" for the scenarios analyzed and "X" for the scenario not considered (see: Table 1) in this study.

25. *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' comment. As suggested, we have changed the title of Table 2 as "Sector specific alternative options for high-GWP hydrofluorocarbons considered in the GAINS model".

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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 CO_2 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 detailed point by point replies to the questions. Referee comments are quoted in italics and authors' responses in blue. 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 CO_2eq 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 CO_2, CH_4, SO_2, NOx, $PM_{2.5}$ 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 ^{o}C (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 CO_2 and CH_4 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 as shown in Table 1 below. Except HFC-23 and HFC-236fa, GWP_{100} is lower than GWP_{20}.

In the revised version of the manuscript, we have added the following paragraph on why we have chosen to use GWP_{100} (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 (GWP_{100}) without climate–carbon feedback effects to convert the varying atmospheric lifetimes and warming potentials for different HFC species to CO_2eq 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 CO_2 reductions. However, these changes could be counterproductive, and the benefits are overstated[1]. 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 CO_2 reductions for every unit amount of reduced short-lived greenhouse gas.

Table 1. Lifetime and GWP of refrigerants (IPCC/AR5)

Type of refrigerant	Lifetime (Years)	GWP 20 years	GWP 100 years
HFC-23	222	10800	12400
HFC-32	5.2	2430	677
HFC-125	28.2	6090	3170
HFC-134	9.7	3580	1120
HFC-134a	13.4	3710	1300

[1]https://climateanalytics.org/briefings/why-using-20-year-global-warming-potentials-gwps-for-emission-targets-is-a-very-bad-idea-for-climate-policy/ accessed on 09/06/2020

HFC-143	3.5	1200	328
HFC-143a	47.1	6940	4800
HFC-152a	1.5	506	138
HFC-245fa	7.7	2920	858
HFC-365mfc	8.7	2660	804
HFC-43-10mee	16.1	4310	1650
HFC-227ea	38.9	5360	3350
HFC-236fa	242	6940	8060

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 °C (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 CO_2? 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).

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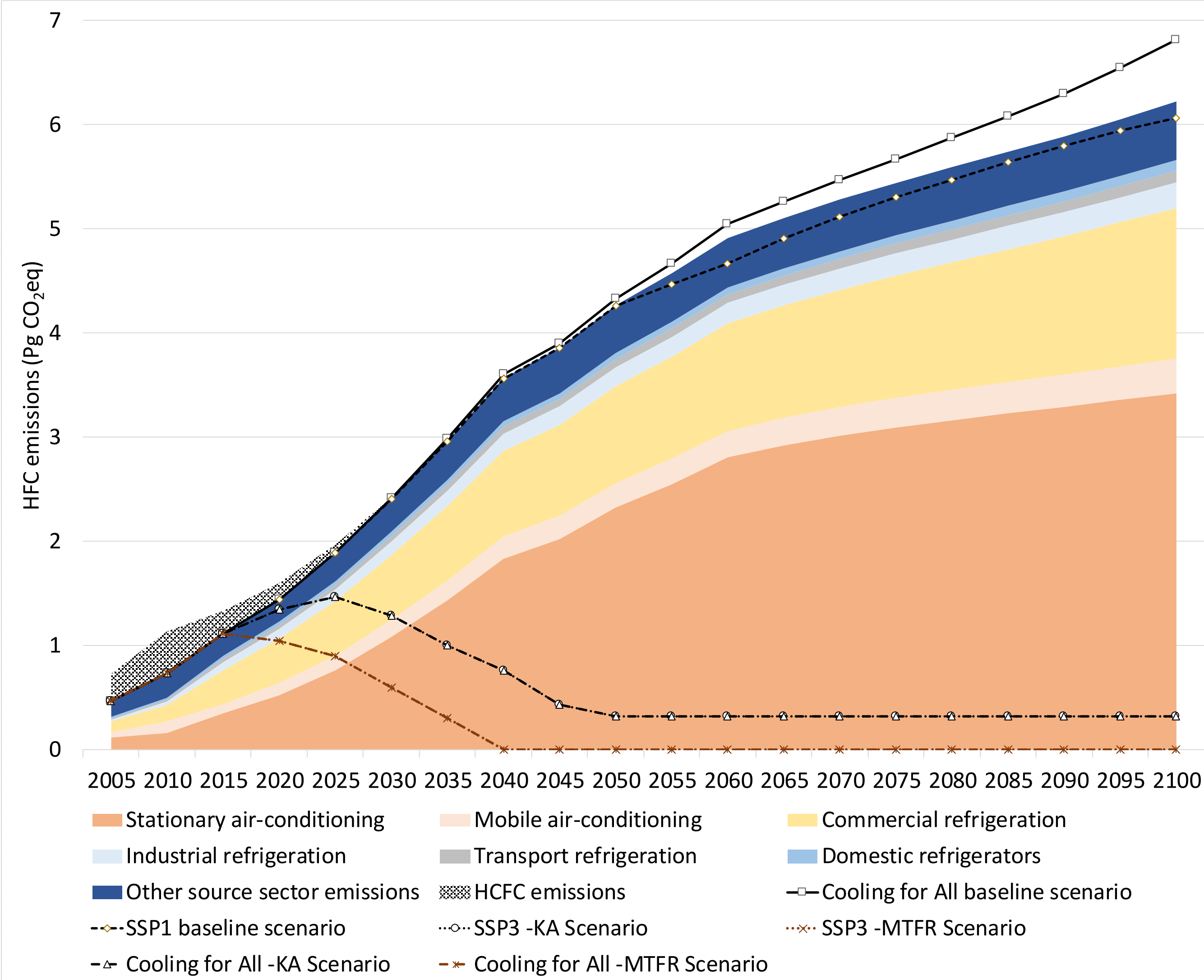

Figure 1: Pre-Kigali SSP3 baseline HFC emissions (with baseline SSP1 and *Cooling for All* shown for comparison) and respective alternative scenarios (Kigali Amendment -KA and Maximum Technically Feasible Reduction -MTFR). Note that *Cooling for All* -KA and *Cooling for All* -MTFR scenarios are not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

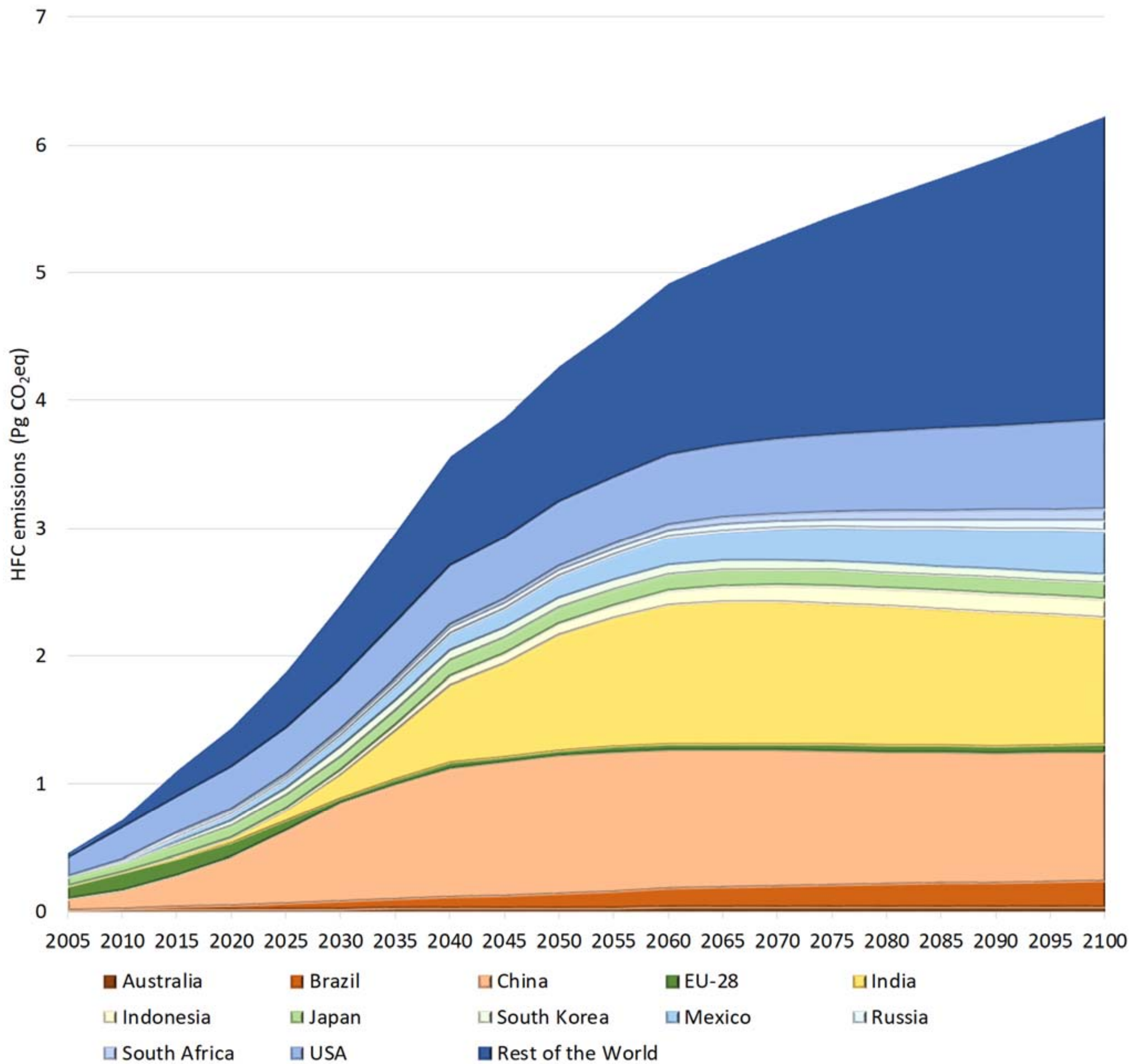

Figure 2: Pre-Kigali SSP3 baseline HFC emissions by regions

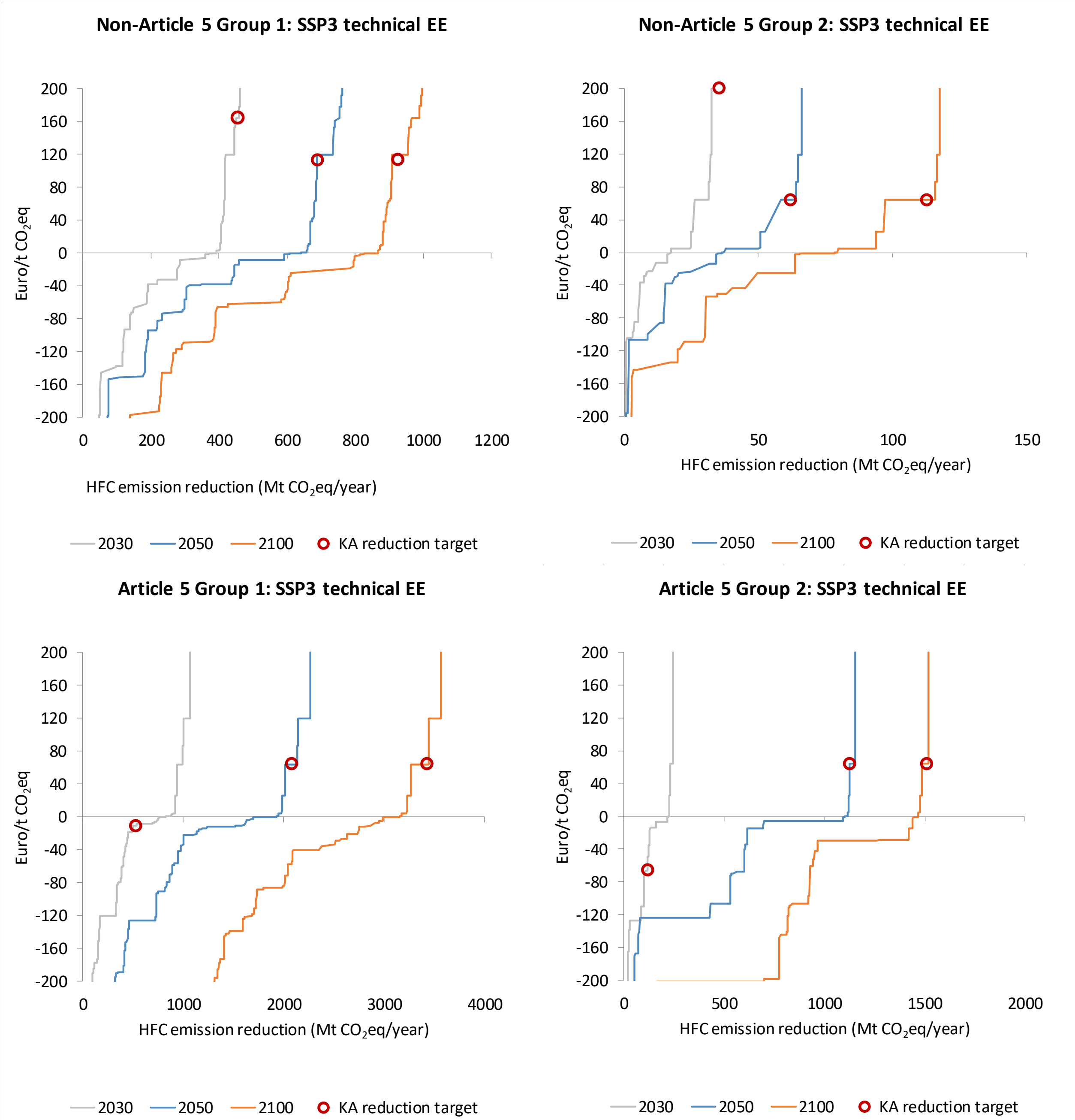

Figure 3: Marginal abatement cost curves (MACCs) starting from a pre-Kigali SSP3 baseline consistent with the IEA-WEO17 New Policies scenario and reducing HFC emissions by Kigali Amendment (KA) party groups under technical energy efficiency improvements and indicating the KA HFC reduction targets in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

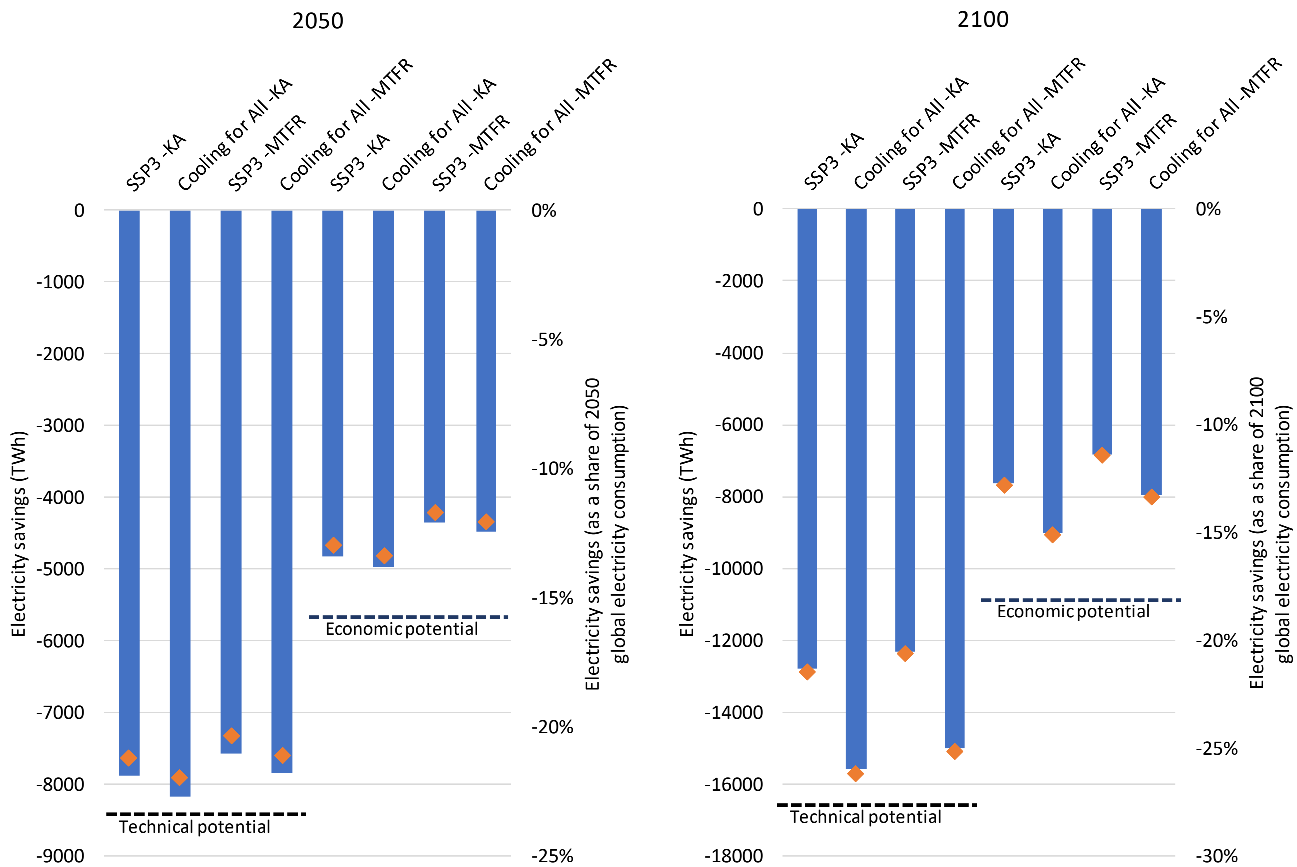

Figure 4: Annual electricity saving potentials when moving from pre-Kigali baselines (SSP3 and *Cooling for All*) to HFC reduction scenarios (Kigali Amendment -KA and Maximum Technically Feasible Reduction -MTFR), in absolute TWh (blue bars) and as a fraction of expected future global electricity consumption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

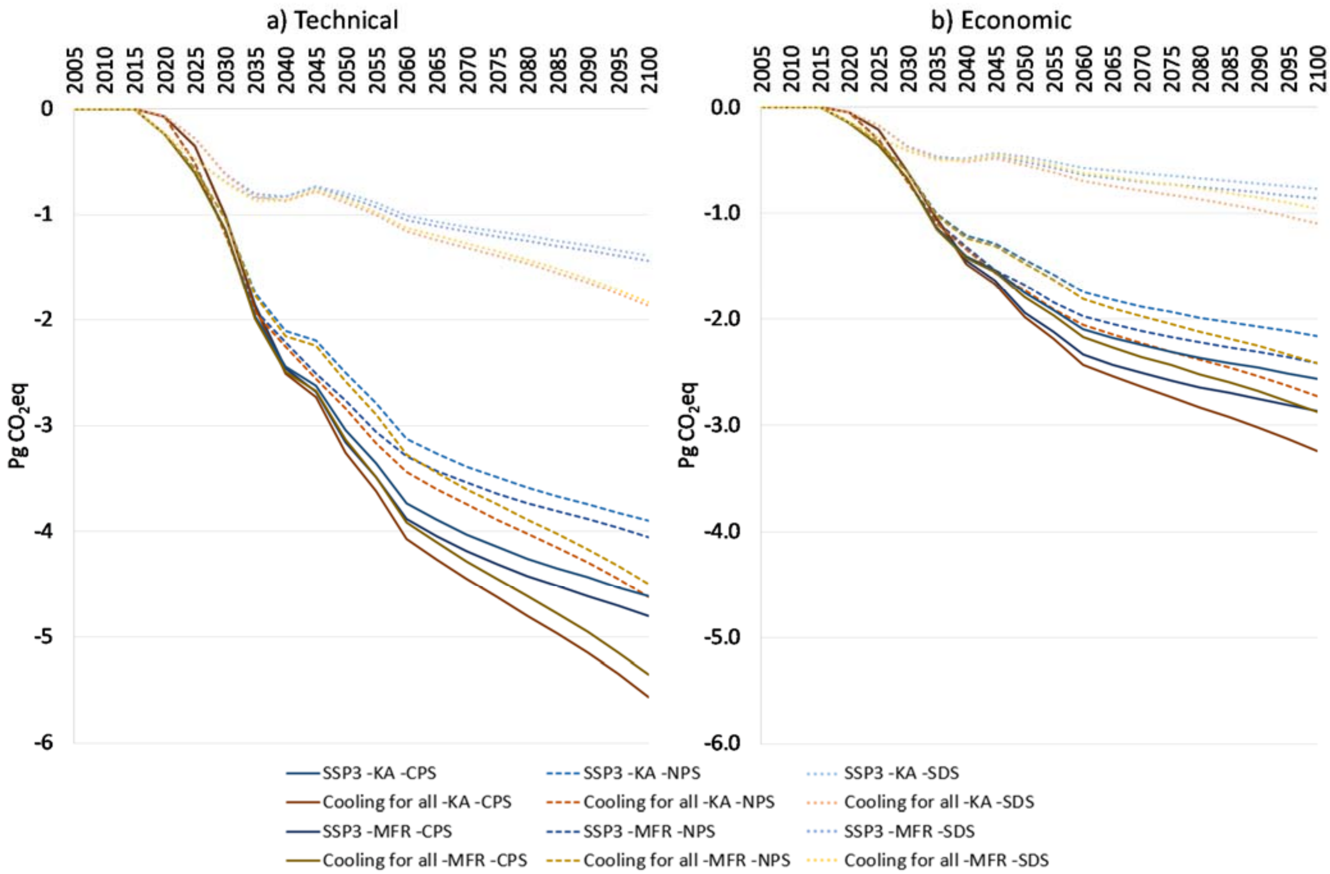

Figure 5: Annual greenhouse gas emission reductions from electricity savings in the Kigali Amendment (KA) and Maximum Technically Feasible Reduction (MTFR) scenarios relative the pre-Kigali baseline scenarios (SSP3 and *Cooling for All*). Results for technical energy efficiency improvements are shown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

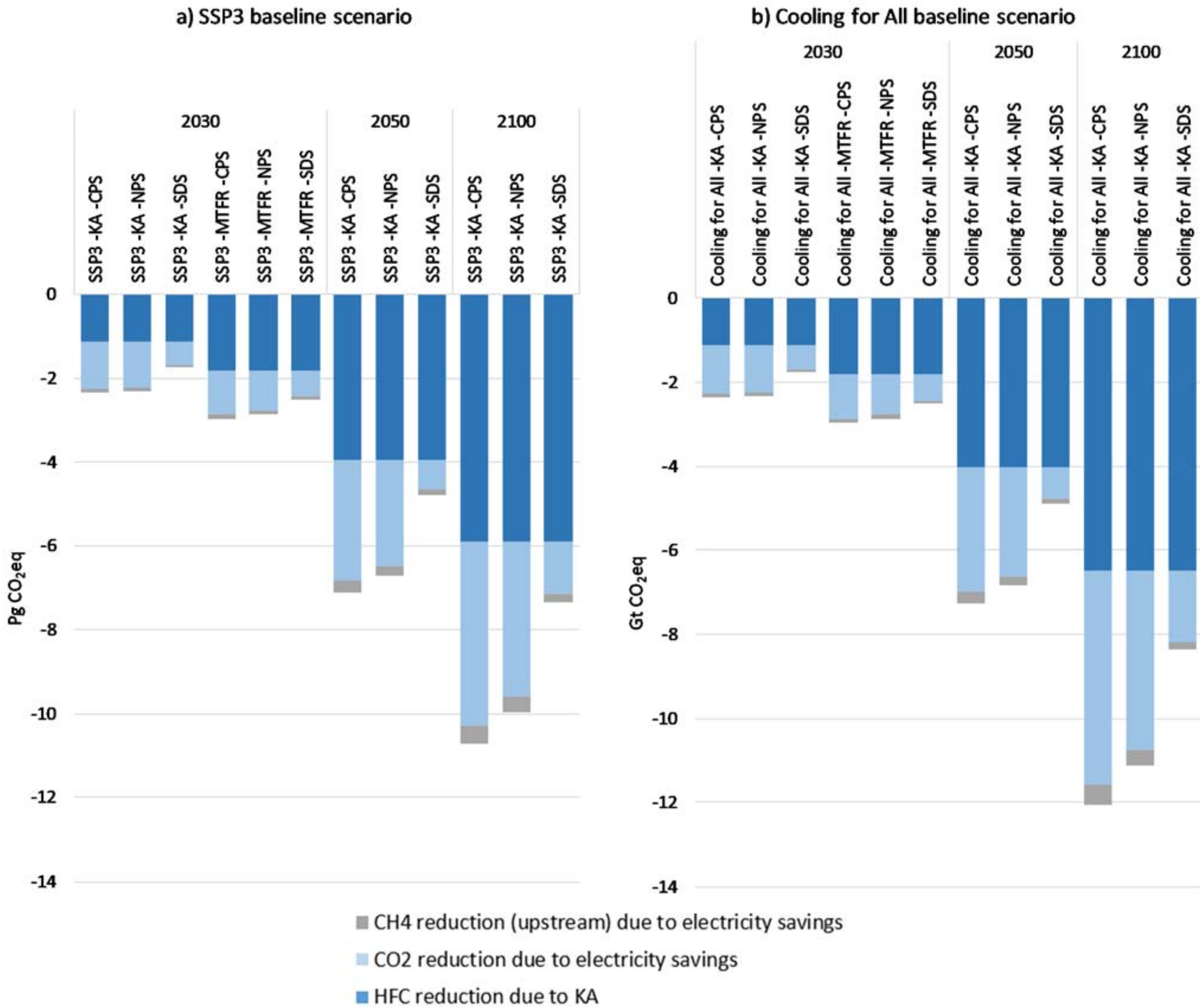

Figure 6: Greenhouse gas mitigation (in Pg CO_2eq) due to enhanced energy efficiency benefits under Kigali amendment (KA) in the alternative scenarios with respect to the a) SSP3 baseline scenario and b) *Cooling for All* baseline scenario. In 2050 and 2100 differences between KA and Maximum Technically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

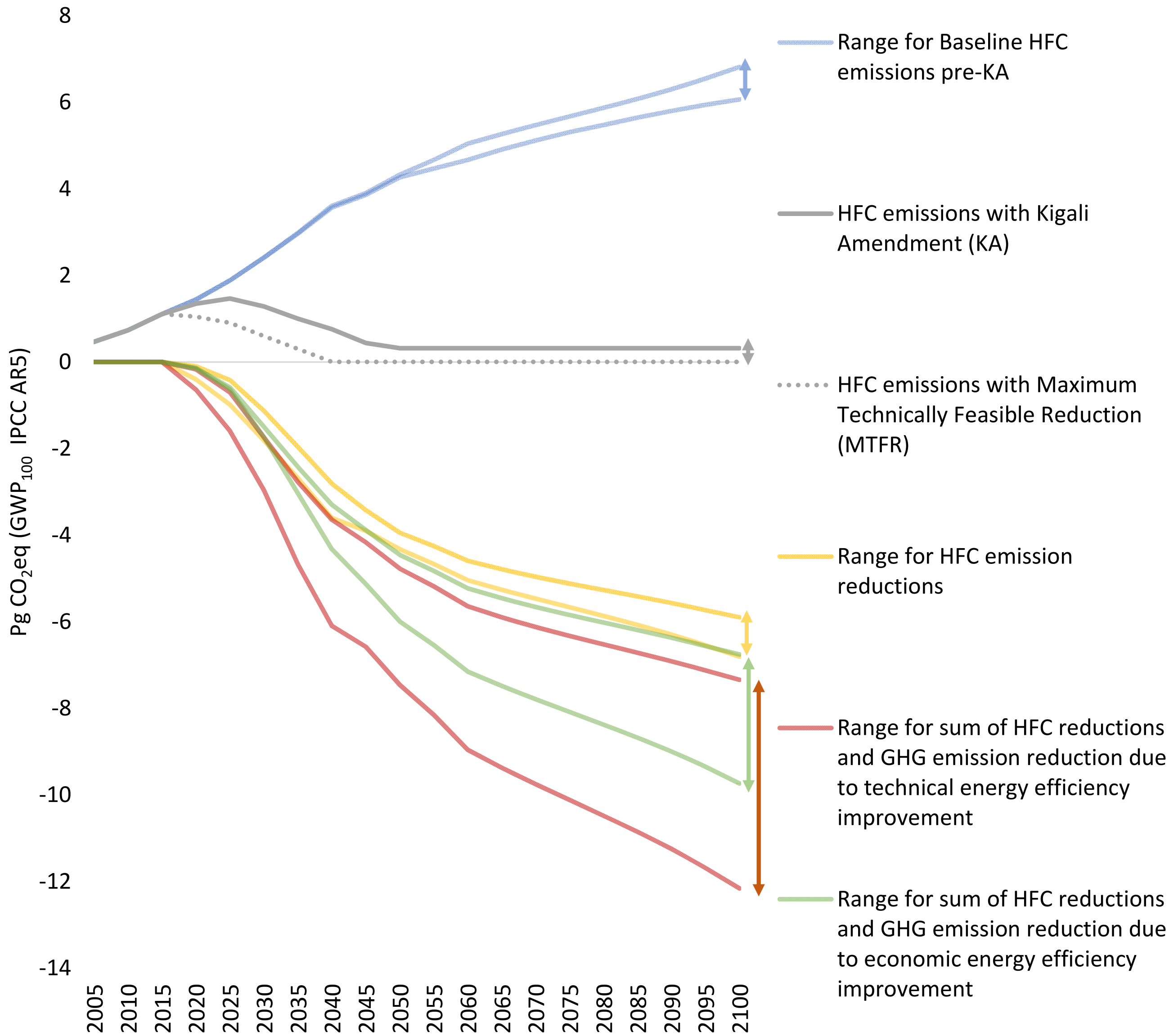

Figure 7: Full range of HFC emissions and mitigation potential under baselines and Kigali Amendment (KA) and Maximum Technically Feasible Reduction (MTFR) scenarios along with HFC and other greenhouse gas mitigation under technical and economic energy efficiency improvement scenarios analysed in this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

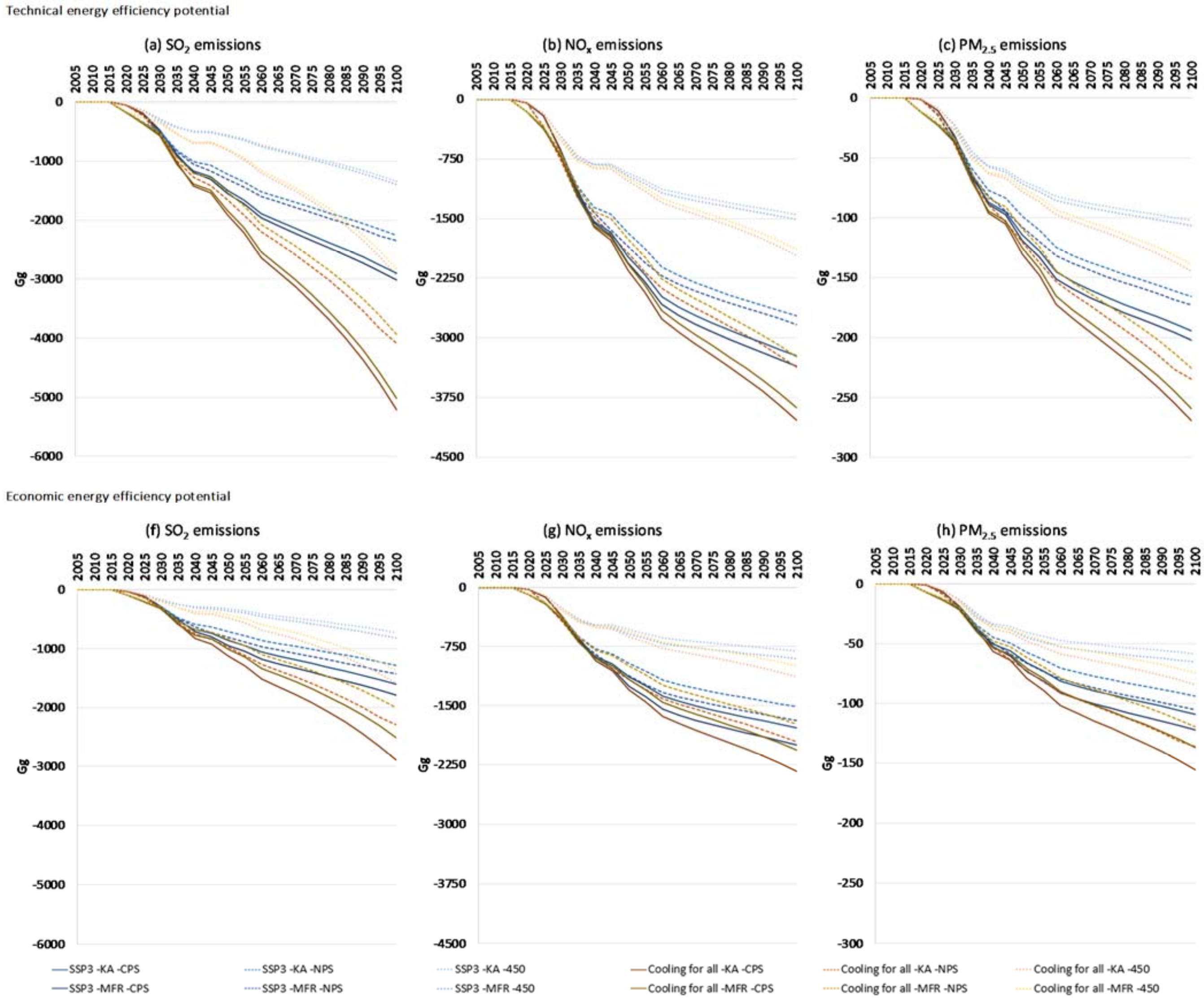

Figure 8: Impacts on air pollutant emissions due to electricity savings associated with alternative HFC phase-down pathways.

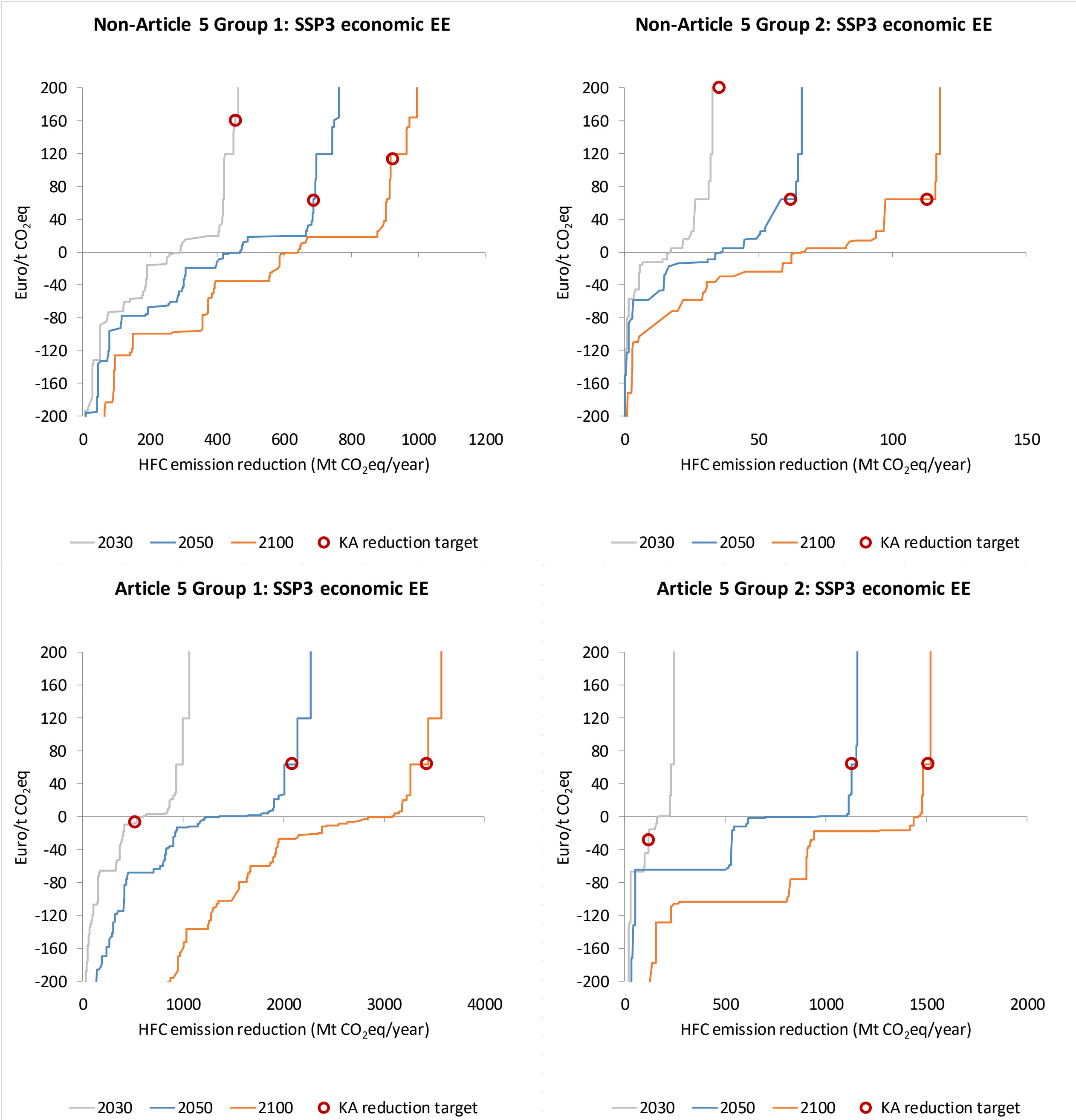

Figure S4: Marginal abatement cost curves (MACCs) starting from a pre-Kigali SSP3 baseline consistent with the IEA-WEO17 New Policies scenario and reducing HFC emissions by Kigali Amendment (KA) party groups under economic energy efficiency improvements and indicating the KA HFC reduction targets in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

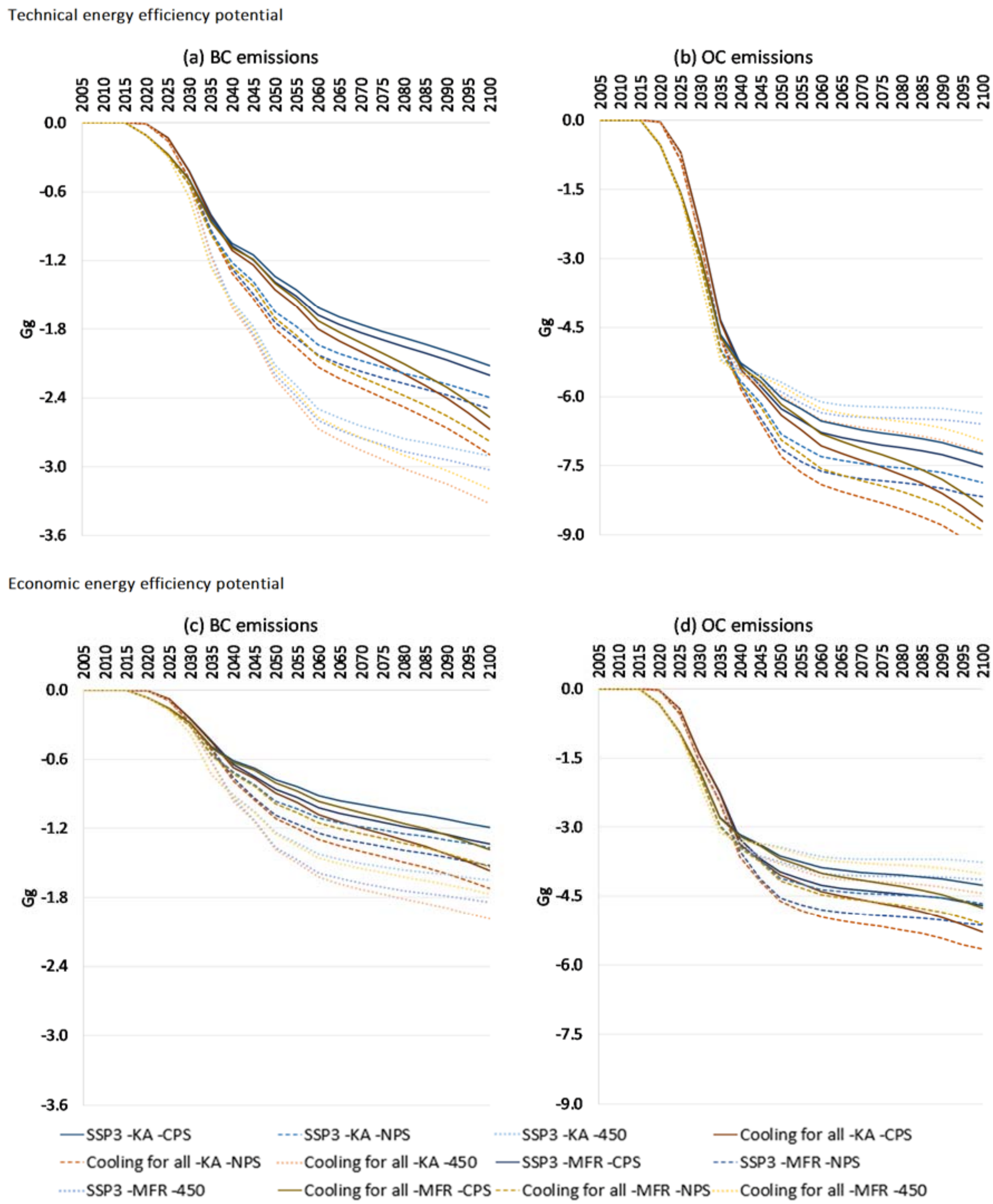

Figure S8: Impacts on BC/OC emissions due to electricity savings associated with alternative HFC phase-down pathways.

Electricity savings and greenhouse gas emission reductions from global phase-down of hydrofluorocarbons

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Abstract. Hydrofluorocarbons (HFCs) are widely used as cooling agents in refrigeration and air conditioning, as solvents in industrial processes, as fire extinguishing agents, for foam blowing and as aerosol propellants. They have been used in large quantities as the primary substitutes for ozone-depleting substances regulated under the Montreal Protocol~~ (MP).~~. However, many HFCs are potent greenhouse gases (GHGs) and as such subject to global phase-down under the Kigali Amendment (KA) to the ~~MP.~~Montreal Protocol. In this study, we develop a range of long-term scenarios for HFC emissions under varying degrees of stringency in climate policy and assess co-benefits in the form of electricity savings and associated reductions in GHG and air pollutant emissions. Due to technical opportunities to improve energy efficiency in cooling technologies~~ during the phase-down of HFCs~~, there exist potentials for significant electricity savings under a well-managed phase-down of HFCs. Our results ~~show that annual pre-KA baseline emissions of HFCs are expected to increase from almost 0.5 to about 4.3 Gt CO_2eq between 2005 and 2050 and reach between 6.2 and 6.8 Gt CO_2eq in 2100. The growth is driven by a strong increase in demand for refrigeration and air conditioning services, which in turn is driven by an expected increase in per capita wealth in developing countries and a warmer future climate. We estimate that full compliance with KA means cumulative global HFC emissions that are 87% lower than in the pre-KA baseline between 2018 and 2100. Also,~~reveal that the opportunity to simultaneously improve energy efficiency in stationary cooling technologies ~~during such a transition~~ could bring ~~about~~ additional climate benefits of about the same magnitude as that attributed to the HFCs phase-down~~ of HFCs~~. If technical energy efficiency improvements are fully implemented, the resulting electricity savings could exceed ~~a fifth~~20% of future global electricity consumption~~.~~, while the corresponding figure for economic energy efficiency improvements would be about 15%. Together with a HFC phase-down, this means preventing between ~~390~~411 and ~~640 Gt~~631 Pg CO_2 equivalent of GHG emissions between 2018 and 2100, thereby making a significant contribution towards keeping the global temperature rise below 2°C. Reduced electricity consumption also means lower air pollution emissions in the power sector, estimated at about 5-10% for sulphur dioxide (SO_2~~,~~), 8-16% for nitrogen oxides (NO_x) and 4-9% for fine particulate matter ($PM_{2.5}$) emissions~~,~~ compared with a pre-~~KA~~Kigali baseline.

1 Introduction

Hydrofluorocarbons (HFCs) are widely used as cooling agents in refrigeration and air conditioning, as solvents in certain industrial processes, as fire extinguishing agents, for foam blowing and as aerosol propellants. As well, HFC-23 is generated as a by-product of chlorodifluoromethane (HCFC-22) production ~~for feedstock and emissive use.~~used in refrigerants and as a chemical feedstock for manufacturing synthetic polymers. HFC emissions have increased significantly in recent years in response to increased demand for cooling services and the phase-out of ozone-depleting substances ~~(ODS)~~ under the Montreal Protocol ~~(MP)~~ (UNEP, 2007; Velders et al., 2009, 2012, 2015; Gschrey et al., 2011; Fang et al., 2016, 2018; Purohit and Höglund-Isaksson, 2017). Many HFCs are potent greenhouse gases (GHGs) with a global warming potential (GWP) up to 12400 times that of CO_2 per mass unit (IPCC, 2013). As users phase out chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) under the ~~MP~~Montreal Protocol, they have often made choices between high-GWP HFC alternatives and alternatives that are more climate-friendly, e.g., hydrocarbons, ammonia, pressurized carbon dioxide and unsaturated HFCs (i.e., hydrofluoroolefins or HFOs in short). In particular countries subject to Article 5 under the ~~MP~~Montreal Protocol (i.e., developing countries) now have the opportunity to leapfrog from the current use of HCFCs and HFCs to alternative technologies with low global warming potential (low-GWP) that are often also more energy efficient (UNEP, 2016a).

The Kigali Amendment (KA) to the ~~MP~~Montreal Protocol agreed in October 2016 and which entered into force on January 1, 2019[1], is a global agreement to phase down and ~~close to~~almost eliminate the consumption of HFCs by 2050 (UNEP, 2016b). Under the KA ~~agreement~~, countries have been attributed to four different party groups~~,~~[2] (Table S1), in which each is subject to an emission reduction schedule outlining target reduction over the next three decades. While previous ~~MP~~Montreal Protocol agreements have resulted in improvements in the design and energy performance of equipment (IPCC/TEAP, 2005), the KA is the first time that maintaining and/or enhancing the energy efficiency of equipment is explicitly included as a goal (EIA, 2016). Hence, the environmental impact of a transition away from HFCs is not only associated with the radiative properties and lifetime of the cooling agents, but also with the lower carbon dioxide (CO_2), methane (CH_4), and ~~associated~~ air-pollution emissions ~~of~~associated with the reduced energy used to power the cooling equipment over its entire lifetime. The switch to low-GWP cooling technology accordingly offers an opportunity to redesign equipment and improve its energy efficiency (UNEP~~/CCAC, 2016~~, 2016a). Much due to a lack of detailed estimations at the sector/technology- and HFC species levels, there is currently limited understanding of the potential future impacts of the KA on global warming and possible co-benefits from savings in electricity (Shah et al., 2019). This study is, as far as we are aware, the first attempt to try to quantify the

[1] Ninety-five signatories have ratified the Kigali Amendment to the Montreal Protocol on phasing down HFCs worldwide until 12th June 2020 (UN, 2020).

[2] The Montreal Protocol Parties are split into four Kigali Amendment groups: a) Non-Article 5, earlier start - Most non-Article 5 countries; b) Non-Article5, 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.

overall effects of the KA on both greenhouse gas and air pollutant emissions. Similarly, there is a need to better understand the implications of going beyond the KA targets and aiming at a close to complete phase-out of HFC emissions globally at an earlier point in time than required under the KA. Addressing these knowledge gaps is the purpose of this study.

The Greenhouse gas - Air pollution Interactions and Synergies (GAINS) model developed by the International Institute for Applied Systems Analysis (IIASA) has previously been used to produce detailed future scenarios for HFC emissions to 2050 (Höglund-Isaksson et al., 2017; Purohit and Höglund-Isaksson, 2017), which have fed into climate models to assess potential impacts on global warming (e.g., UNEP/CCAC, 2018; Rogelj et al., 2018; UNEP, 2017; Gambhir et al., 2017). This study extends on previous work by producing long-term scenarios of HFC emissions to the year 2100 under varying degrees of stringency in climate policy, and by assessing potential co-benefits in the form of savings in electricity and associated reductions in greenhouse gas and air pollution emissions.

The paper is set out as follows: Section 2 presents the methodology used to generate baseline and alternative scenarios for HFC emissions and for estimating potentials for electricity savings in the cooling sector. Section 3 presents the low-GWP options considered as replacements for the use of high-GWP HFCs in the GAINS model. Section 4 presents results while Section 5 concludes the key findings ~~of the study.~~.

2 Methodology

2.1 Baseline scenarios

For the purpose of this study, baseline scenarios for global HFC emissions have been developed under the assumption that the KA is not implemented. Although pre-KA baseline scenarios may be seen as outdated and therefore uninteresting given that the KA has already entered into force[3], it is still necessary to first generate baselines as consistent bases for the construction of future emission reduction scenarios. The demand for cooling is here expressed in terms of equivalent mass units of HFCs consumed. The starting point is the current consumption of HFCs by species and sector as reported by countries to the United Nations Framework Convention on Climate Change (UNFCCC) or derived in the GAINS model using a consistent methodology (Purohit and Höglund-Isaksson, 2017). To the extent that alternative technologies are already adopted due to existing national and regional regulations (see: Section S1 of the Supplementary Information (SI)), impacts are reflected in both historical HFC consumption levels and in future baseline scenarios. Future demand for HFCs in a pre-KA setting is projected using population, macroeconomic variables (GDP and value added from industry and services) and cooling degree days (CDDs) as drivers and under the assumption that the use of HFCs for cooling continues into the future. The pre-KA baseline scenarios provide a primary point of reference for evaluating the need for, and impact of, alternative technologies. Hence, the mitigation scenarios developed here assume the same demand for cooling services as in the respective baselines,

[3] ~~Ninety-three signatories have ratified the Kigali Amendment to the Montreal Protocol on phasing down HFCs worldwide until 24th February 2020 (UN, 2020).~~

but with the consumption of high-GWP HFCs replaced by alternative low-GWP technologies. The choice and order of adoption of technologies in a given sector are determined by marginal abatement cost curves (MACC) estimated on the basis of baseline HFC consumption (Höglund-Isaksson et al., 2017). For descriptions of key drivers at the sectoral level, source-specific emission factors and implemented control policies, see the supplementary material of Purohit and Höglund-Isaksson (2017).

The baseline scenarios improve upon those presented in Purohit and Höglund-Isaksson (2017) and Höglund-Isaksson et al., (2017) not only by extending the scenarios to 2100, but also by making use of the information on historical HFC consumption by sector and HFC species that has recently become available at increasingly greater detail from the Nationalnational reporting to the UNFCCC. The principal information sources used to estimate historical HFC consumption and emissions are: 1) robust historical HFC consumption data by sector (2005, 2010 and 2015) for developed countries derived from their UNFCCC National Inventory Submissions (UNFCCC, 2017); 2) historical HFC consumption data for China and India and with some additional information for other developing countries from various national and international sources[4]; 3) data on historical HCFC consumption from UNEP (2017), part of which has been replaced by HFCs; and 4) assumed effective control of HFC-23 (CHF3) emissions from the manufacture of HCFC-22 (CHClF2) in China (Simmonds et al., 2018; UNEP, 2018) and India (GoI, 2016; Say et al., 2019). From these compiled datasets, historical HFC consumption is derived for 174 countries/regions and for 14 separate source sectors (including aerosols, commercial refrigeration, domestic refrigerators, fire extinguishers, ground source heat pumps, HCFC-22 production for emissive and feedstock applications, one component and other foams, industrial refrigeration, mobile air-conditioning, solvents, stationary air-conditioning (including commercial and residential), and transport refrigeration), and 13 different HFC species (HFC-23, HFC-32, HFC-125, HFC-134, HFC-134a, HFC-143, HFC-143a, HFC-152a, HFC-245fa, HFC-365mfc, HFC-43-10mee, HFC-227ea, HFC-236fa). Blends of HFCs have been decomposed and attributed to respective HFC species. In this study, we apply IPCC AR5 global warming potentials (GWPs) over 100 years without climate–carbon feedback effects when converting the warming potential for different HFC species to CO_2eq units (IPCC, 2013).[5]. Moreover, the commercial refrigeration and air-conditioning sectors are subdivided into small and large systems to allow for adoption of different low-GWP alternatives for small and large units in mitigation scenarios. The same level of detail at the country-, sector- and HFC species levels as for historical emissions, are maintained in the construction of future emissionsemission scenarios.

In this study, we have chosen to follow the convention of the policy community to use IPCC global warming potentials over 100 years (GWP_{100}) without climate–carbon feedback effects to convert the varying atmospheric lifetimes and warming potentials for different HFC species to CO_2eq 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

[4] Including HFC inventories prepared by Climate & Clean Air Coalition (CCAC) and United Nations Development Programme (UNDP), UNEP Ozone Secretariat, non-Annex-I parties national communication to the UNFCCC, etc.

[5] For e.g., HFC-410A is a zeotropic mixture of 50% HFC-32 and 50% HFC-125. Similarly, HFC-407C is a zeotropic mixture of 23% HFC-32, 25% HFC-125, and 52% HFC-134a.

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 GWP_{100} 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.

For the development of the baseline scenarios in the timeframe to 2040, we use the existing model setup in GAINS, which for global scenarios uses drivers consistent with macroeconomic and energy sector projections from the IEA World Energy Outlook 2017 (IEA-WEO, 2017)[6]. To reflect the emission impact range of a continued fossil-fuel driven development relative a decarbonisation of the energy systems, the analysis use implied emission factors from three IEA-WEO2017 scenarios; Current Policies Scenario[7] (CPS), New Policies Scenario[8] (NPS) and Sustainable Development Scenario[9] (SDS). For stationary air-conditioning, the global stock of air conditioners in buildings modelled in GAINS were adjusted to approximate the stocks estimated by the IEA (2018). The extension in demand for cooling services between 2040 and 2100, expressed here in tons of HFC consumed, has been generated in consistency with the growth in population and macroeconomic indicators of the third Shared Socioeconomic Pathway (SSP3) (IIASA, 2017)[10] and the expected future increase in regional CDDs[11] received from IEA (2018). The reason for selecting the SSP3 scenario as the primary driver for the extension to 2100 is that for the period 2005 to 2040 it comes ~~the closest~~close to the IEA-WEO (2017) in terms of growth in global population and GDP levels (see: Figure S1 of the SI). The SSP3 is, however, a relatively pessimistic future scenario with the highest growth in global population and one of the lowest GDP growth rates among all SSP scenarios. We have therefore prepared alternative projections to 2100 using the more optimistic SSP1 scenario as a sensitivity case[12]. The difference in HFC emission projections

[6] GAINS relies on import of externally produced macroeconomic and energy sector projections. In this case, the range of energy sector scenarios produced for the IEA-WEO 2017 was used.

[7] This scenario considers the impact of those policies and measures that are firmly enshrined in legislation as of mid-2017. It provides a cautious assessment of where momentum from existing policies might lead the energy sector in the absence of any other impetus from government.

[8] The NPS aims to provide a sense of where today's policy ambitions seem likely to take the energy sector. It incorporates not just the policies and measures that governments around the world have already put in place, but also the likely effects of announced policies, including the Nationally Determined Contributions (NDCs) made for the Paris Agreement (PA).

[9] This scenario outlines an integrated approach to achieving internationally agreed objectives on climate change, air quality and universal access to modern energy. Further information is available in IEA-WEO (2017) and Rafaj et al. (2018).

[10] The SSPs are based on five narratives describing the alternative socio-economic developments “sustainable development” (SSP1), “middle-of-the-road development” (SSP2), “regional rivalry” (SSP3), “inequality” (SSP4), and “fossil-fueled development” (SSP5) (Riahi et al., 2017).

[11] 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).

[12] 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 among 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.

compared to the SSP3, turned out to be minimal. Since the mitigation potential relative the baseline is similar for different SSP scenarios, this kind of sensitivity analysis only brings added value in a baseline setting (addressing a variation in baseline demand for cooling services). The SSP1 scenario is therefore not analysed in a mitigation context.

Exposure to health risks due to extreme temperatures have been growing worldwide (Mueller et al., 2016; Pal and Eltahir, 2016; Mora et al., 2017; Russo et al., 2017) and a significant number of heat related deaths are reported annually during the summer months in both the northern and southern hemispheres, particularly among the elderly, the poor, and in densely populated cities (Mastrucci et al., 2019). Global heat stress is projected to increase in a 1.5°C warmer world (IPCC, 2018). Compared to a 1961–1990 level, climate change could by 2030 be responsible for additional annual deaths of 38,000 people from heat stress, particularly among the elderly (WHO, 2014). Each 1°C increase could reduce work productivity by 1-3% for people working outdoors or without air conditioning, typically the poorer segments of the workforce (Park et al., 2015). The increased use of air conditioning enhances resilience to heat stress (Petkova et al., 2017). However, due to its high cost, air conditioning is considered a luxury, and only 8% of the 2.8 billion people living in the world's hottest regions possess an air conditioning unit today (IEA, 2018). In addition, almost one billion people lack access to electricity (IEA, 2019) and at least one billion live in slum conditions (World Bank, 2019), both of which make access to space cooling challenging. Cooling contributes significantly to peak load and is therefore an important consideration when deciding on capacity of electricity networks (Shah et al., 2015). The lack of access to essential indoor cooling is a major equity issue and is increasingly seen as a dimension of energy poverty and wellbeing that demands attention from policymakers. Therefore, in parallel with the SSP3 baseline scenario and drawing on previous work by IEA (IEA, 2018), a *Cooling for All*[13] scenario has been developed, which is an alternate baseline scenario that focuses on how we embed growing cooling demands that can reach everyone within a clean energy transition, and in turn, support faster progress to achieve the goals of the KA. In this alternate baseline scenario, we do not model demand for cooling services in the residential sector only as a function of population, macroeconomic drivers, and changes in CDDs, but assume in addition that in countries/regions with ~~average~~ climates on average exceeding 1000 CDDs[14], the uptake of residential air conditioners is at least one per household by 2050 (and takes place irrespective of income constraints). Similarly, the uptake of domestic refrigerators in the *Cooling for All* scenario is assumed to be at least one per household by 2050 irrespective of income constraints.

Energy efficient buildings, shading, cool/green roofs etc. could substantially reduce HFC and electricity consumption in residential and commercial buildings (Goetzler et al., 2016). However, in this study we have not considered such options,

[13] The *Cooling for All* initiative (IEA, 2018) focuses on how we provide sustainable access to cooling within a clean energy transition, and in turn, support faster progress to achieve the goals of the Kigali Amendment ~~to the Montreal Protocol, agreed on in Rwanda in 2016.~~.

[14] For regions with CDD<1000 it is assumed that the households will use other cooling appliances (e.g. fan, evaporative coolers, etc.) if they cannot afford room air-~~conditioner~~conditioners. By 2050, approximately 183 million households (or nearly 1 billion people) in hot countries will have at least one air-conditioner in the *Cooling for All* scenario ~~as compared to the SSP3 baseline scenario.~~.

partly due to a lack of detailed information about their potential at the country level and partly due to the focus of this study on direct replacement of current and future use of HFCs with alternative substances.

~~Effective~~ Furthermore, effective cooling is essential to preserve food and medicine (Peters, 2018). The increased demand for cooling to preserve food in a warmer world, including the associated increase in electricity consumption, are considered in the baseline scenarios for emissions developed here. Extended refrigeration of food would also mean reduced food losses, which apart from having important implications for meeting nutritional needs, would also contribute to reduced greenhouse gases from food production and better use of the 23–24% of global cropland and fertilizers currently used to produce food that is eventually ~~lost~~wasted (Kummu et al., 2012; Hiç et al., 2016). Hence, reducing global food supply chain losses have several important secondary benefits including conservation of energy and other resources (Kummu et al., 2012) as these are freed up to be converted into other productive activities (Ingram, 2011; Beddington et al., 2012; Kummu et al., 2012; Hiç et al., 2016; Lamb et al., 2016). Due to a lack of detailed information on impacts on food supply chains, such secondary benefits from extended use of industrial and commercial refrigeration and refrigerated transport are not considered in this study.

2.2 HFC reduction scenarios

We develop alternative HFC reduction scenarios in consistency with the demand for cooling modelled in the pre-KA baseline scenarios described in Section 2.1. The key contribution of this task is not to determine the reduction levels in HFC consumption (as these are already pre-determined by the regional targets of the KA and by the almost complete reductions possible under MTFR), but to investigate the content of the HFC phase-down in terms of ~~to what~~the order and extent ~~the~~to which various alternative technologies ~~identified~~ are picked up in the different sectors and regions. This is important as it is only by understanding the content of the low-GWP technology uptake that we can get an idea of the expected degree of employment of different technologies and their respective contributions to electricity savings and reductions in GHGs and air pollution, which tend to differ by region, sector and technology (Höglund-Isaksson et al., 2017).

The order of technology uptake to meet the KA targets is determined by the marginal abatement cost curves~~,~~ (MACCs), which for a given technology and sector are defined using country-, sector-, and year- specific information (Höglund~~-~~-Isaksson et al., 2016; 2017). For example, the variation in unit costs reflects variations between countries and over time in electricity prices and ~~labor~~labour costs. For this study, we have used ~~marginal abatement cost curves (MACC)~~MACCs to simulate technology uptake every five years until 2050 and assume the relative employment of technology in 2050 to remain constant until 2100 at the country- and sector- level. Given the high uncertainty about future technology developments, we find that it does not make much sense to model individual technology uptake in greater detail than this in the period post 2050. To model the sector technology uptake required to meet the KA, we have produced emission scenarios with cost curves including all HFC source sectors, i.e., in addition to cooling, we also include HFC emissions from aerosols, foams, industrial processes and other sources. This is necessary because the relative contribution of each sector towards the predetermined regional reduction targets (see: Section S2 of the SI) can only be determined when all HFC sectors are included in the analysis. Note that for given technology options, potential effects of future technological development on costs~~, HFC removal~~ and the efficiency ~~and energy~~

efficiencyin reducing the climate impact of cooling when replacing HFCs, have not been considered here. As the removal of HFCs is close to complete withIt 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 technologyalternative low-GWP measures, and costs are not assessed at the absolute level but for the sole purpose of cost estimates isusing MACCs to determine the order of technology uptake, inclusion of technological. Technological development effects will not affect conclusions regarding the HFC phase-down. However, not considering potential technological development effects on future could also mean even larger potentials for energy efficiency improvements than those considered here as technical and economic potentials. Not considering this hear may be considered a conservative assumption and may result in even higher, as there could be some potentials for futureeven larger electricity savings in the future.

Once we have determined the types of technology and the extent to which they are expected to be employed in different countries and sectors, we can start quantifying the electricity savings and associated CO_2 and air pollution reductions expected from several of the technology switches that replace the use of HFCs. Hence, in addition to the direct climate benefits of HFC emission reductions, transitioning away from HFCs can catalyzecatalyse additional climate benefits through improvements in the energy efficiency of the refrigerators, air conditioners, freezers, and other products and equipment that currently use HFCs. Historically, refrigerant conversions, driven by refrigerant phase-outs under the MPMontreal Protocol, have catalyzedcatalysed significant improvements in the energy efficiency of refrigeration and A/CAC systems—up to 60% in some subsectors (Zaelke et al., 2013). Similar improvements are expected under an HFC phase-down following the KA targets. For example, recent demonstration projects for utilizing low-GWP alternatives to HFCs presented by the Climate and Clean Air Coalition (CCAC) calculated energy savings of 15-30% and carbon footprint reductions of 60-85% for refrigeration in commercial food stores (Borgford-Parnell et al., 2015; UNEP/CCAC, 2016, 2016a). According to three research studies completed in Brazil, inverter units using lower GWP refrigerants can save up to 67% energy compared to fixed speed units with high GWP RHFC-410A (UNEP/TEAP, 2019). Energy-related emissions can be reduced with lowered cooling demands, more efficient equipment, and operating strategies that maximize system performance (Calm, 2006; Mills, 2011; Sharma et al., 2014; Shah et al., 2015; Purohit et al., 2016; Dreyfus et al., 2017; Sharma et al., 2017; Zaelke and Borgford-Parnell, 2015; IEA, 2018; Purohit et al., 2018b; Park et al., 2019).; Godwin and Ferenchiak, 2020). Shah et al. (2013) find that even the best currently available technology offers large efficiency improvement opportunities (35-70% reduction in energy consumption from the market average) in room air-conditioners. The current cost-effective efficiency improvements range from 20% to -30% reduction in energy consumption based onfrom a consumer perspective. Based on their operating profiles, even small efficiency improvements translate into significant reductions in GHG emissions (Phadke et al., 2014). Goetzler et al. (2016) estimated 73–-76% of global CO_2eq emissions from air-conditioning systems in 2010 to be indirect emissions from the energy use. Recent estimates based on scientific assessments of ozone depletion indicate that improvements in energy efficiency in refrigeration and air-conditioner equipment during the KA transition to low-GWP alternative refrigerants, can potentially double the climate benefits of the HFC phase-down (WMO, 2018). In addition to energy efficiency improvements from technical adjustments of the cooling equipment (viz. stationary air-conditioning, commercial, domestic, industrial and transport refrigerators), there is also expected ~~to be~~ a small potential for energy efficiency improvement from the transition of high-GWP into low-GWP HFCs for given cooling equipment (Schwarz et al., 2011; Barrault et al., 2018; Shah et al., 2019). Both these sources of energy efficiency improvements are considered in this study, while only the latter ~~were~~was considered in Purohit and Höglund-Isaksson (2017) and Höglund-Isaksson et al. (2017).

For the purpose of this study, information on expected energy efficiency improvement potentials through technical adjustments in stationary cooling equipment, were provided by the Lawrence Berkeley National Laboratory (See: Table S2 of the SI). Two different sets of assumptions were provided~~;~~: a "technical" and an "economic" energy efficiency potential. The former reflects ~~an~~the efficiency improvement potential considered technically possible, i.e., representing an upper limit for expected energy efficiency improvements, while the latter reflects ~~an efficiency improvement considered economically profitable and represents~~ a minimum energy efficiency improvement~~. No similar information on expected~~ that is considered economically profitable. Note that energy efficiency improvements take place also when HFCs are replaced in mobile air ~~conditioning~~conditioners (MAC) ~~was provided and such improvements have therefore~~(Blumberg et al., 2019). These are however not ~~been considered~~accounted for here as the drivers for associated emission changes are very different from those in ~~this study. Note~~stationary sources and more complex to estimate. Note also that while building design and urban planning can significantly reduce heating or cooling load[15] (IEA, 2013), such options were not considered in this study as the focus here is on energy efficiency enhancements due to uptake of alternative cooling technologies to replace HFCs. ~~Note also~~Finally, note that the technical losses of electricity in transmission and distribution (T&D) segments have been taken into account (Brander et al., 2011) whereas non-technical losses (NTL)[16] e.g. due to theft, have not been considered in the estimation of electricity saving potentials. Table S2 of the SI provides information on the unit energy consumption (UEC) of stationary cooling technologies identified by LBNL and how these have been interpreted in this study in terms of energy efficiency improvement potentials in different sectors/technologies when moving from a pre-KA baseline to low-GWP alternative scenarios.

Lower electricity consumption translates into reduced emissions of GHGs, i.e., CO_2~~,~~ from fuel use and fugitive CH_4 from fuel production, storage and distribution, and air pollutants such as sulphur dioxide (SO_2~~,~~), nitrogen oxides (NO_X) and particulate matter below 2.5 µm ($PM_{2.5}$~~, and~~), and black and organic carbon (BC/OC). BC/OC, CH_4 and HFCs are short-lived climate pollutants (SLCPs) ~~such as black and organic carbon (BC/OC) and methane (CH_4).~~with stronger warming impacts in the short- than long run. While reductions in greenhouse gas emissions add to climate change mitigation, co-benefits in the form of

[15] The building envelope determines the amount of energy needed to heat and cool a building, and hence needs to be optimized to keep heating and cooling loads to a minimum. A high-performance building envelope in a cold climate requires just 20-30% of the energy required to heat the current average building in the Organisation of Economic Co-operation and Development (OECD). In hot climates, the energy savings potential from reduced energy needs for cooling are estimated at between 10% and 40% (Dreyfus et al., 2017).

[16] Technical losses occur naturally due to power dissipation in transmission lines, transformers etc. Electricity theft forms a major chunk of the NTL that includes illegal tapping of electricity from the feeder, bypassing the energy meter, tampering with the energy meter and several physical methods to evade payment to the utility company (Depuru et al., 2011).

reduced air pollution translate into health and ecosystem improvements (Nemet et al., 2010; Markandya et al., 2018; Vandyck et al., 2018). Commercial and residential buildings are known to use more electricity on hotter days (Schaeffer et al., 2012; Valor et al., 2001). The electricity generation unitsplants (e. g. coal, oil and gas fired power plants) that respond to this increased demand are major contributors to sulfur dioxide (SO_2) and nitrogen oxides (NOx emissions (IEA, 2016), both of which have direct impacts on public health, and contribute to the formation of secondary pollutants (Amann et al., 2020; Purohit et al., 2019) including ozone and fine particulate matter$PM_{2.5}$. Abel et al. (2017) found a 3.9% increase in electricity generation per °C that was consistent with Sailor (2001) 0.4−5.3% per °C sensitivity range. Further, NOx emissions sensitivity of 3.60 ± 0.49% per °C (Abel et al., 2017) was consistent with range in He et al. (2013) of 2.5-4.0% per °C using similar methodology and region but a different time-period. The atmospheric fate and climate impacts of BC from different regions could differ considerably (Berntsen et al., 2006; Reddy and Boucher, 2007). The net effects of BC and organic carbon (OC) on temperature and precipitation are potentially significant, especially at regional scales, because BC and OC have relatively short atmospheric lifetimes (days to week). These features mean BC/OC are not well mixed in the atmosphere (Bond et al., 2004; Hansen and Nazarenko, 2004; Forster et al., 2007) He et al. (2013) range of 2.5−4.0% per °C using similar methodology and region but a different time period.and therefore not possible to relatively easily convert into CO_2eq terms using GWPs.

The GAINS model contains a database on region country-, sector-, and fuel- specific emission factors for a range of air pollutants and greenhouse gases from energy production and consumption (IIASA-GAINS, 2019). From this source, we take implied emission factors per GWh electricity consumed for each pollutant listed above and in reflection of expected country- and year- specific fuel mixes used in power plants in the respective IEA-WEO 2017 Current Policies Scenario[17] (energy scenarios CPS), New Policies Scenario[18] (, NPS) and Sustainable Development Scenario[19] (SDS), respectively, in the timeframe to 2040 (see: Figure S2 of the SI). While the implied emission factors for all other pollutants but CH_4 reflect country- and year- specific emissions from combustion of fuels in the power sector, upstream CH_4 emissions from extraction, storage and transmissiondistribution of fossil fuels used in the power sector are only assessed at the global level due to a lack of information about future fossil fuel trade flows. Hence, the implied emission factors for CH_4 reflect global year-specific factors consistent with the weighted average of upstream CH_4 emissions embedded in an average unit of electricity consumed. Note that the SDS represents a low carbon scenario consistent with a 2 °C2°C (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. Detailed implied emission factors are available from IIASA's GAINS model only in the timeframe to 20502040. The country-specific

[17] This scenario only considers the impact of those policies and measures that are firmly enshrined in legislation as of mid-2017. It provides a cautious assessment of where momentum from existing policies might lead the energy sector in the absence of any other impetus from government.

[18] The NPS aims to provide a sense of where today's policy ambitions seem likely to take the energy sector. It incorporates not just the policies and measures that governments around the world have already put in place, but also the likely effects of announced policies, including the Nationally Determined Contributions (NDCs) made for the Paris Agreement (PA).

[19] This scenario outlines an integrated approach to achieving internationally agreed objectives on climate change, air quality and universal access to modern energy. Further information is available at IEA-WEO (2017) and Rafaj et al. (2018).

implied emission factors for air pollutants per GWh electricity consumed representative for year ~~2050~~2040 have therefore been kept constant over the entire period ~~2050~~2040 to 2100.

In conclusion, Table 1 summarizes the 31 different scenarios generated and analyzed in this study. As outlined in Section 2.1, there are three pre-KA baseline scenarios: Baseline –SSP1, Baseline –SSP3, and a *Cooling for All* baseline. The Baseline – SSP3 and the *Cooling for All* baseline have been used as starting points for four alternative HFC reduction scenarios; a Kigali Amendment (KA) scenario, a KA high Energy Efficiency (KA-EE) scenario, a Maximum Technically Feasible Reduction (MTFR) scenario, and a MTFR high Energy Efficiency (MTFR-EE) scenario. The high Energy Efficiency scenarios are specified for the "technical" and "economic" energy efficiency improvement potentials described above. For each of the four HFC reduction scenarios with energy efficiency improvements, global and regional estimates of expected electricity savings and associated impacts on ~~CO_2 emissions, ~~GHGs and air pollutants ~~and SLCPs ~~have been estimated assuming compliance with the KA targets and under ~~maximum technically feasible reductions (~~MTFR~~)~~. Finally, for each high EE scenario, three variants of implied emission factors for GHGs (CO_2 and CH_4) and air pollutants have been used reflecting the three IEA-WEO 2017 energy scenarios, namely, the CPS, NPS and SDS. In this way, the future air pollution projections span a wide range of possible future energy sector developments.

The KA scenarios (KA and KA-EE) have been developed to analyze the implications of achieving the HFC phase-down targets set out in the KA and specified for four different country/party groups. For each group, the relative HFC phase-down targets differ due to different baselines, HFC consumption freeze years and HFC phase-down schedules (see: Section S2 of the SI). The sector-specific mitigation strategy identified for each of the four KA party groups is determined by the respective ~~marginal abatement cost curves~~MACCs (Höglund~~-~~-Isaksson et al., 2017). Savings on electricity costs make up an important part of the abatement cost. ~~Because of the~~This study assumes larger potentials for energy efficiency improvements ~~assumed here compared with ~~than in Höglund-Isaksson et al. (2017~~),~~) and marginal abatement costs are therefore generally lower~~ in this study.~~. Accordingly, a revised set of ~~marginal abatement cost curves~~MACCs have been generated for all HFC sectors, by each party group, and for each five-year interval to understand the expected technology compositions after countries have taken action to meet the KA targets. The MTFR scenarios have been developed to assess the maximum ~~technically feasible ~~reduction of HFCs~~ at the sectoral and regional levels~~ when not considering cost constraints, but assuming the same sets of energy efficiency improvements as outlined in the KA-EE scenarios. ~~The abatement potentials in both the KA and MTFR scenarios reflect reductions in emissions through the application of technologies that are currently commercially available and already tested and implemented, at least to a limited extent. Apart from improvements in energy efficiency, there is no further improvement assumed in terms of technology removal efficiency of HFCs (which is anyway complete or close to complete in most sectors) or in terms of investment and non-energy related operation and maintenance costs.~~

3 Alternatives to high-GWP HFCs

To avoid the use and emissions of both HFCs and HCFCs, a variety of climate-friendly, energy efficient, safe and proven alternatives are available today (UNEP, 2011; CCAC, 2019). In fact, for most applications where HFCs and HCFCs are still used~~ in the world~~, more climate friendly alternatives can be ~~used~~found. However, due to different thermodynamic and safety properties of the alternatives, there is no "one size fits all" solution applicable to all equipment categories. The suitability of a certain alternative must be evaluated for each category of product and equipment and also taking account of the level of ambient temperature at the location where the product and equipment is being used and other factors such as safety codes and flammability ratings (Abdelaziz et al., 2016; Purohit et al., 2018a).

In recent years, there has been a focus on natural refrigerants (pressurized CO_2, hydrocarbons, and ammonia), low-GWP HFCs, ~~as well as on unsaturated HFCs (also known as~~and HFOs~~)~~ used alone or in blends with ~~saturated~~ HFCs to replace fluids with high-GWP~~.~~ (Beshr et al., 2015; McLinden et al., 2017; Heredia-Aricapa et al., 2020). A recent increased use of hydrocarbons (e.g., iso-butane and propane), ammonia, and pressurized carbon dioxide is expected to continue into the future~~.~~ (UNEP, 2016a). Many of these alternatives are widely used in non-Article 5 countries in response to national or regional regulations that require reductions in HFC use. ~~Many of these technologies are starting to become available in Article 5 countries and the level of~~The availability and uptake is rapidly increasing~~.~~ also in Article 5 countries (Reese, 2018; UNEP, 2019). Table 2 lists alternatives that are currently used on a commercial scale and considered in the GAINS model for assessing mitigation potentials. Moreover, the model considers good practice measures: leakage control during use and recovery of the refrigerant after end-of-life of the equipment.

4 Results and Discussion

4.1 HFC emissions

Pre-KA baseline HFC/HCFC emissions consistent with the macroeconomic development of the IEA-WEO 2017 in the period 2005-2040 and with the SSP3 in the period ~~2050~~2040-2100, are presented in Figure 1. For historical years 2005, 2010 and 2015, the contribution from HFC emissions to global greenhouse gas emissions are estimated at 0.46, 0.73 and 1.1 ~~Gt~~Pg CO_2eq, respectively, with an additional 0.27, 0.40 and 0.23 ~~Gt~~Pg CO_2eq release of HCFCs in the respective years. In 2010, 22% of HFC emissions are released from stationary air conditioning, 15% as HFC-134a from mobile air conditioners, 31% from commercial, industrial, transport and domestic refrigeration, 18% as HFC-23 emissions from HCFC-22 production for emissive and feedstock use, and 14% from use in aerosols, foams, solvents, fire-extinguishers and ground-source heat pumps. Hence, stationary cooling equipment releases more than half of global HFC emissions.

Between 2005 and 2050, pre-KA baseline HFC emissions are estimated to increase by a factor of nine, as shown in Figure 1. The growth is mainly driven by a twelve-fold increase in demand for refrigeration and air-conditioning services, which in turn is driven by an expected increase in per capita wealth in developing countries combined with the effect of replacing CFCs and

HCFCs with HFCs in accordance with the revised ~~MP~~Montreal Protocol preceding the KA. Under the revised ~~MP~~Montreal Protocol, HCFCs in emissive use should be virtually phased out by 2030, but still allowing for servicing of the existing stock until 2040. Baseline HFC emissions are expected to increase to 4.3 ~~Gt~~Pg CO_2eq in 2050 and to 6.2 ~~Gt~~Pg CO_2eq in 2100. The slower increase in the second half of the century is due to saturation in many markets. The expected pre-KA baseline HFC emissions in 2050 are within the range (4.0-5.3 ~~Gt~~Pg CO_2eq) of previous estimates by Velders et al. (2015).

As shown in Figure 2, rapid growth in pre-KA baseline emissions is expected in Article 5 (mainly developing) countries with an approximately eleven-fold increase between 2005 and 2100. China is expected to contribute one-quarter of global HFC emissions in 2050, closely followed by India (21%). Between 2050 and 2100, HFC use in China and India is increasingly saturated and these two countries emit about one third of global HFC emissions in 2100. For the EU-28, pre-KA baseline HFC emissions in 2050 are lower than in 2005 due to implementation of stringent F-gas regulations, whereas corresponding emissions in the USA increase by a factor of two under existing regulations.

HFC emissions per capita in residential air-conditioning and domestic refrigeration sectors in the SSP3 and *Cooling for All* pre-KA baseline scenarios are presented in Table 3. Due to the increased penetration of room air-conditioners and domestic refrigerators in the *Cooling for All* baseline scenario, HFC emissions per capita in Article 5 parties are 7% and 36% higher in 2050 and 2100, respectively, as compared to the SSP3 baseline scenario.

Figure 1 also presents global pre-KA HFC baseline emissions by key cooling sectors in the three baseline scenarios discussed in Section 2 (including also SSP1). In the *Cooling for All* baseline scenario, HFC emissions could reach 6.8 ~~Gt~~Pg CO_2eq by 2100, driven primarily by an increased cooling demand in the residential sector. As a sensitivity case, HFC emissions in the SSP1 baseline scenario reach 6.1 ~~Gt~~Pg CO_2eq by 2100. Hence, the SSP3 pre-KA baseline emissions fall between the *Cooling for All* and the SSP1 baseline scenarios. In the SSP3 -KA scenario, HFC emissions decline gradually over the analysed period reaching 92% and 95% removal of pre-KA baseline emissions on an annual basis in 2050 and 2100, respectively. Faster emission reductions than those mandated by the ~~Kigali Amendment~~KA represent an additional opportunity for climate change mitigation (Cseh, 2019). The SSP3 -MTFR scenario (lower dashed line) shows that it is considered technically feasible for KA party groups to move earlier in terms of emission reductions and to remove more than 99% of annual emissions in the period 2035 to 2100. Figure S3 presents the HFC/HCFC emissions under the pre-KA baseline and alternative scenarios by different party groups.

Table 4 presents the corresponding cumulative emissions over the entire period 2018 to 2100. At the global level, cumulative HFC emissions are estimated at 363 ~~Gt~~Pg CO_2eq in the pre-KA SSP3 baseline scenario and at 378 ~~Gt~~Pg CO_2eq in the pre-KA *Cooling for All* baseline scenario. In the sensitivity case using the SSP1 drivers, global cumulative HFC emissions are estimated at 355 ~~Gt~~Pg CO_2eq, which is about 2% less than in the SSP3 baseline scenario. For both the SSP3 and *Cooling for All* baseline scenarios, stringent compliance with the KA is expected to reduce cumulative HFC emissions by 87% below baseline, whereas ~~maximum technically feasible implementation of abatement technology (MTFR) is~~ the expected ~~to reduce~~ cumulative reduction in MTFR is nearly 97% below baseline ~~emissions by 96-97%. Over the period 2018-2100, this~~. This converts into cumulative HFC emissions of 48 ~~Gt~~Pg CO_2eq when complying with the KA and 13 ~~Gt~~Pg CO_2eq if implementing MTFR. For respective KA party groups, the relative reductions in cumulative emissions 2018-2100 ranges between 84-93% for full compliance with the KA and between 94-99% for full implementation of MTFR. The lower range values represent party groups with countries that already have legislation implemented to limit the use of HFCs~~, while the upper range values represent the reduction potential for party groups with countries that currently do not regulate HFC use.~~. 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 KA entering into force (Section S1 of the SI).

4.2 Cost curves

Figure 3 shows the estimated marginal abatement cost curves for global HFC emission reductions under technical ~~and economic~~ energy efficiency potentials in 2030, 2050 and 2100, respectively. The curves describe the marginal abatement cost paths between the pre-KA baseline and the MTFR emission levels. The red circles in Figure 3 indicate the respective points at the cost curves where the KA targets are being met. For Article 5 countries, there are low cost or even negative (i.e., net profitable) cost options available to meet the KA targets until 2030 due to large potentials to improve on the energy efficiency in cooling technologies. The more ambitious KA targets for 2050 and 2100 are, however, expected to come at a positive marginal cost and would accordingly require implementation of additional policy incentives. The marginal abatement cost for achieving the ~~Kigali~~KA targets is relatively high for non-Article 5 countries in 2030 due to low cost options already adopted in response to ~~the~~existing F-gas regulations ~~already implemented at the regional and national levels~~ in many developed countries (Section S1 of SI). Similarly, Figure S4 of SI presents the MACCs for global HFC emission reductions under economic energy efficiency potentials in 2030, 2050 and 2100, respectively. The abatement potential extends over time, primarily due to the expected increase in pre-KA baseline emissions but also due to a gradual phase-in of alternative technology in the short run as technical and economic barriers prevent an immediate full uptake of available technology. Net savings on abatement costs are primarily expected from replacing HFCs with NH_3 in industrial refrigeration, switching from HFCs to propane (HC-290) in residential air conditioning, substituting HFCs for isobutane (HC-600a) in domestic refrigerators, replacing HFCs with hydrocarbons (HC-290) in vending machines, using pressurized CO_2 in remote and integral display cabinets in commercial refrigeration, switching from HFCs to CO_2-based systems in transport refrigeration, and switching from high to low-GWP HFCs (e.g., HFC-152a) or CO_2-based systems in foam blowing.

4.3 Co-benefits due to HFC phase-down with enhanced energy efficiency

4.3.1 Electricity savings

Figure 4 presents the technical and economic electricity saving (TWh) potentials when moving from the pre-KA baselines (SSP3 and *Cooling for All*) to corresponding alternative scenarios (KA and MTFR). Globally, the annual technical and economic electricity saving potentials under the KA are estimated at 7882 and 4821 TWh, respectively, in 2050 relative the SSP3 baseline scenario. The annual electricity saving potentials almost double in absolute terms by 2100 as compared to 2050.

In the *Cooling for All* scenario the annual technical electricity saving potential are slightly higher than in the SSP3, reaching 8169 TWh in 2050 and 15595 TWh in 2100. The annual technical and economic electricity saving potentials in the alternative scenarios (KA and MTFR) by different party groups are illustrated in Figure ~~S4~~S5 and Table S3 of the SI. Note that in the MTFR scenarios, the estimated technical potential is slightly smaller than in the KA. The reason is that the KA scenario is constructed assuming uptake of technologies (to meet the KA reduction targets) in the order of increasing marginal cost for HFC replacement. Options at the very high end of the marginal abatement cost curve (e.g., pressurized CO_2) have slightly lower warming potentials than hydrocarbons~~ and HFOs~~, but also use more electricity (Groll and Kim, 2007; Astrain et al., 2019). It is accordingly an effect of technology switches at the very high end of the marginal abatement cost curve~~ for HFC removal~~, e.g., hydrocarbons and HFOs replaced by pressurized CO_2.

For illustrative purposes, Figure ~~5~~4 also displays a comparison of future annual electricity savings to the total global consumption of electricity as estimated for years 2050 and 2100 in the AIM/CGE SSP3 baseline scenario (Riahi et al., 2017). As shown, if the full technical potential to improve energy efficiency in cooling is implemented as part of efforts to comply with the KA targets, the electricity savings would make up 26% and 22% of expected global electricity consumption in 2050 and 2100, respectively. If only the economic potential to improve energy efficiency in cooling is implemented, the corresponding savings would make up 15% and 13% of expected global electricity consumption in 2050 and 2100, respectively. Hence, the future electricity saving potentials in the cooling sector are significant.

4.3.2 Impacts on greenhouse gas emissions

~~The~~Figure 4 shows how electricity~~-~~ savings ~~presented in Figure 4 can be converted to~~convert into approximate reductions in GHG (CO_2 and CH_4) emissions from electricity generation ~~if we combine them with implied emission factors for CO_2 and CH_4 that reflect~~in the ~~expected country- and year- specific fuel mixes used in power plants in the~~respective IEA-WEO 2017 energy scenarios CPS, NPS and SDS~~, respectively~~ (see also Figure S2 of the SI). Figure ~~6~~5 presents GHG emission reductions in the alternative (KA and MTFR) scenarios due to electricity savings induced by HFC phase-down and under full implementation of technical (Panel a) and economic (Panel b) energy efficiency improvements, respectively, as well as for a range of implied emission factors deriving from the CPS, NPS and SDS~~, respectively.~~ energy scenarios. CH_4 reductions have here been converted into CO_2eq units and added to reductions in CO_2 emissions. The corresponding GHG emission reductions using technical and economic electricity saving potentials by different KA party groups are presented in Figures ~~S5~~ S6 ~~of the SI.~~

~~Compliance with the KA and full realization of the technical energy efficiency improvement potentials, mean annual reductions in global CO_2 emissions estimated at 1.4 Gt in 2050 and 4.4 Gt in 2100 relative~~and S7. Relative a pre-KA SSP3 baseline scenario and using GAINS implied emission factors derived for the ~~IEA-WEO 2017~~ CPS energy scenario~~. For the same set~~, compliance with the KA and realization of the full technical energy efficiency improvement potentials convert into annual greenhouse gas emission reductions from electricity savings of 3 Pg CO_2eq in 2050 and 5.5 Pg CO_2eq in 2100. Out of ~~assumptions~~these, annual ~~global methane (CH_4)~~reductions in CO_2 emissions from ~~extraction of fossil fuels used in the power~~

~~plant sector~~reduced fuel use are estimated ~~lower by~~at 1.4 Pg CO_2 in 2050 and 4.4 Pg CO_2 in 2100, while the corresponding reductions in annual global CH_4 emissions from extraction, storage and distribution of fossil fuels are estimated at 9 and 15 ~~Mt~~Tg CH_4 in 2050 and 2100, respectively~~, relative the pre-KA SSP3 baseline scenario~~. This corresponds to about two percent of expected business-as-usual CH_4 emissions from global anthropogenic sources in 2050 (Höglund-Isaksson et al., 2020). Greenhouse gas savings when realizing the full economic potential for electricity savings are estimated at about half of the reductions from realizing the full technical potential. As expected, the corresponding annual CO_2 mitigation relative the *Cooling for All* baseline is slightly larger at 1.5 ~~Gt~~Pg CO_2eq in 2050 and 5.1 ~~Gt~~Pg CO_2eq in 2100~~ than for the SSP3 baseline~~. The estimated reductions in CO_2 and CH_4 emissions from electricity savings are lower when using implied emission factors derived for the IEA-WEO17 NPS and SDS energy sector scenarios than for the CPS, because of higher ~~penetrations~~penetration of clean fuels (gas, renewables etc.) and uptake of energy efficiency measures in the power sector.

~~Converting CH_4 reductions into CO_2eq units using GWPs over 100 years without climate-carbon feedback effects (IPCC, 2013) and adding these to the CO_2 reductions allow for calculating total reductions in greenhouse gas emissions due to electricity savings when reducing HFCs to comply with the KA. These are illustrated in Figure 6 for the technical (panel a) and economic (panel b) potentials for energy efficiency improvements. Depending on the energy sector development (CPS, NPS or SDS), annual greenhouse gas emission reductions due to realization of the full technical potential for energy efficiency improvements in cooling are assessed at between 0.8 and 3 Gt CO_2eq in 2050 and between almost 2 and 5.5 Gt CO_2eq in 2100. Greenhouse gas savings when realizing the economic potential for electricity savings are estimated at about half of that.~~

We can also convert the reduction in HFC emissions into CO_2eq terms ~~using GWPs over 100 years without climate-carbon feedback effects (IPCC, 2013). Adding these~~ and add these to the GHG reductions ~~to those~~ from electricity savings, ~~give~~which gives us an estimate of total reductions in greenhouse gas emissions due to a phase-down of HFCs. These are shown in Figure ~~7~~6 with GHG reductions relative a pre-KA SSP3 baseline shown in ~~Panal~~Panel a) and relative a pre-KA *Cooling for All* baseline shown in Panel b). Results are presented for all the variants of future energy sector development pathways considered (i.e., CPS, NPS and SDS). Compared to a pre-KA baseline, meeting the KA means total annual GHG emissions ~~being~~are lower by between 4.8 and 7.3 ~~Gt~~Pg CO_2eq in year 2050 and between 7.3 and 12.1 ~~Gt~~Pg CO_2eq in 2100. Table 5 presents the cumulative reductions in overall GHG emissions due to both HFC phase-down and ~~a realization of potential energy efficiency improvements.~~ the associated electricity savings. Results are presented by KA party groups and ~~global. Compliance~~globally for technical and economic energy efficiency improvements. Hence, compliance with the KA targets and full implementation of energy efficiency improvements mean avoiding between 411 and 631 ~~Gt~~Pg CO_2eq of greenhouse gas emissions between 2018 and 2100. 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~~.

Figure 7 summarizes impacts on GHG emissions and presents in the upper half the full range of HFC emissions under the three baselines (SSP1, SSP3 and *Cooling for All*) and the alternative KA/MTFR scenarios. In the lower half, Figure 7 shows the full ranges of HFC mitigation potentials under the alternative KA/MTFR scenarios along with the ranges for the sum of reduction potentials in HFC and other greenhouse gases (CO_2 and CH_4 from electricity savings) induced by a HFC phase-down. The full ranges reflect implementation of technical and economic energy efficiency improvements, respectively, for the ranges of implied emission factors consistent with the CPS, NPS and SDS energy scenarios when meeting the KA targets or under MTFR.

4.3.3 Impacts on air pollution

Other potentially important environmental benefits of reduced demand for electricity in cooling are reduced air pollution and related adverse effects on human health and ecosystems. Figure 8 presents reductions in air pollutant emissions due to electricity savings associated with the alternative (KA and MTFR) scenarios. The upper set of graphs (~~panels~~Panels a-~~e~~c) show emission reductions when technical energy efficiency improvement potentials are fully implemented, while the bottom set of graphs (~~panels~~ Panels d-f~~-j~~) show the corresponding impacts when economic energy efficiency improvement potentials are fully implemented. In 2015, space cooling was responsible for 9% of global emissions of ~~Sulphur dioxide (~~SO_2~~)~~ emissions from the power sector and 8% of ~~nitrogen oxides (~~NOx~~)~~ and ~~fine particulate matter (~~$PM_{2.5}$~~)~~ emissions from the power sector (IEA, 2018). Our results indicate that meeting the KA targets means global SO_2 emissions in the power sector are reduced by 10% and 12% relative the SSP3 and *Cooling for All* baselines, respectively, and when assuming implied emission factors from the CPS ~~development of the~~ energy ~~sector~~scenario (Figure 8a). For the same set of assumptions, annual global NOx emissions in the power sector are expected 16% lower than baseline emissions in 2050 (Figure 8b), while global $PM_{2.5}$ emissions from the power sector are 8% and 9% lower than in the SSP3 and *Cooling for All* baselines, respectively (Figure 8c). Due to a higher penetration of clean fuels in the power sector, reductions in all air pollutant emissions are more limited in the NPS and SDS ~~as compared to the CPS~~ energy ~~sector development.~~scenarios.

Considering the limited contribution of the power sector to total global emissions of these air pollutants, the overall impact on global air pollutant emissions is relatively small at less than 4% according to information on total global emissions in 2050 taken from the GAINS model (IIASA-GAINS, 2019) for the same energy ~~sector development.~~scenario. This small impact makes it difficult to quantify any potential health and ecosystems impacts in a meaningful way.

~~In addition to air pollutants, we have also assessed the impacts on black and organic carbon (~~ Because BC/OC~~) from enhanced energy efficiency in cooling technology. BC/OC are short-lived climate forcers (SLCFs) and as such contribute to global warming. The atmospheric fate and climate impacts of black carbon (BC)~~ emissions~~ from different regions could differ considerably (Berntsen et al., 2006; Reddy and Boucher, 2007). The net effects of BC and organic carbon (OC) on temperature and precipitation are potentially significant, especially at regional scales, because BC and OC have relatively short atmospheric lifetimes (days to week). These features mean BC/OC~~ are not well mixed in the atmosphere ~~(Bond et al., 2004; Hansen and Nazarenko, 2004; Forster et al., 2007)~~ and therefore not ~~possible to relatively~~ easily ~~convert~~converts into CO_2eq ~~terms using GWPs like for other GHGs that are well mixed due to long atmospheric lifetimes. Therefore~~units despite being a SLCP, we present results for BC/OC impacts in Figure ~~8~~S8 instead of together with the impacts on GHGs in Figure ~~7~~6. The results indicate that meeting the KA targets means global BC emissions from the power sector are 4% lower in 2030 and 6% lower in 2050 relative the baseline scenarios (Figure ~~8d~~S8 Panel a). Similarly, global OC emissions from power plants are 13% lower in 2050 relative the baseline scenarios (Figure ~~8e~~S8 Panel b). Considering that the power plant sector accounts for less than 0.5% of global BC and OC emissions from all sources (IIASA-GAINS, 2019), the global impact on these emissions from a HFC phase-down ~~is likely minimal~~range is negligible at 0.03% and 0.065%, respectively.

5 Conclusions ~~and Policy Recommendations~~

Hydrofluorocarbons (HFCs) are ~~widely used~~manufactured to be use as ~~cooling agents in refrigeration and air conditioning, as solvents in certain industrial processes,~~substitutes for ~~foam blowing and as aerosol propellants~~ozone-depleting substances that are being phased out globally under Montreal Protocol regulations. Emissions of HFCs are strong greenhouse gases and as such targeted for reduction to mitigate climate change. The Kigali Amendment (KA) to the Montreal Protocol~~ (MP)~~ from 2016 sets out phase-down pathways to 2050 for the worldwide use of HFCs. Users are encouraged to transition to alternative agents with low global warming potentials~~ (low-GWP).~~. Enhancement of energy efficiency as part of such a transition is a strategic, near-term opportunity to reap significant additional climate and clean air benefits. This study presents long-term scenarios of HFC emissions to the year 2100 under varying degrees of stringency in climate policy and assesses potential co-benefits in the form of electricity savings and associated reductions in greenhouse gas ~~(GHG)~~ and air pollutant emissions through improved energy efficiency in stationary cooling. The following inferences can be drawn ~~based on~~from this study:

- Prior to the commitments made under the KA, baseline annual emissions of HFCs are expected to increase from about 0.5 to 4.3 ~~Gt~~Pg CO_2eq between 2005 and 2050, reaching between 6.2 and 6.8 ~~Gt~~Pg CO_2eq in 2100, depending on whether or not all households in hot climatic conditions install residential air conditioning. The growth is mainly driven by an eighteen-fold increase in demand for refrigeration and air conditioning services, which in turn is driven by an expected increase in per capita wealth in developing countries, a warmer future climate, combined with the effect of replacing chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) with HFCs in accordance with the 2007 revision of the Montreal Protocol. Cumulative HFC emissions over the ~~entire~~ period 2018 to 2100 are estimated at 363 and 378 ~~Gt~~Pg CO_2eq in respective baseline scenarios. This is a considerable share of the entire future budget of less than 800 ~~Gt~~Pg CO_2eq that IPCC (2018) estimates as available for the world to remain well below 2 °C warming above the pre-industrial level.
- Full compliance with the commitments made by parties to the KA through replacement of HFCs with low-GWP alternatives~~,~~ (e.g. hydrocarbons, hydrofluoroolefins, ammonia, water, CO_2), means cumulative HFC emissions of less than 50 ~~Gt~~Pg CO_2eq between 2018 and 2100. With maximum technically feasible implementation of existing control technology and without the delays in implementation built into the KA, cumulative HFC emissions could be as low as 13 ~~Gt~~Pg CO_2eq between 2018 and 2100, thereby removing about 97% of cumulative pre-KA baseline emissions.
- If carefully addressed during the transition to low-GWP alternatives, improvement potentials for energy efficiency in cooling technologies are extensive and can bring significant electricity savings. ~~We estimate compliance with the KA~~

When fully implementing the technical potential for energy efficiency improvements~~ in cooling~~, we estimate that compliance with the KA can bring electricity savings that correspond to more than 20% of the world's entire future electricity consumption. With the energy efficiency improvements limited to the economically profitable applications, electricity savings in cooling could still make up as much as 15% of future electricity consumption.

- Compliance with the KA means avoiding between 441 and 631 ~~Gt~~Pg CO_2eq of greenhouse gas emissions between 2018 and 2100. 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 policy-makers address energy efficiency improvements in cooling technology simultaneously with requirements ~~to substitute the use of HFCs with low-GWP alternatives~~for HFCs substitution.
- Electricity savings also mean reduced air pollutant emissions from the power sector with ~~related~~associated positive effects on human health and ecosystems. We estimate that meeting the KA targets while also implementing the full technical potential for energy efficiency improvements in cooling technologies, can lower future global sulphur dioxide (SO_2) emissions from the power sector by up to 10%-12%. Corresponding future impacts on nitrogen oxides (NOx) emissions from power plants are 16% lower ~~emissions in the power sector~~ relative the baselines and 8-9% lower for fine particulate matter ($PM_{2.5}$) emissions. Considering that the power sector accounts for a smaller share of global emissions of SO_2, NO_x and $PM_{2.5}$, the overall impact of electricity savings in cooling on global air pollutant emissions is less than 4%. The impact on global black carbon (BC) and organic carbon (OC) emissions is~~ even smaller, 6% and 13% lower emissions from the power sector in 2050. Considering that the power sector contributes less than 0.5% to global BC and OC emissions from all anthropogenic sources, the impact on these emissions from electricity savings in cooling are~~ negligible.

A key policy finding is the importance of paying careful attention to the electricity-savings that can be reaped in the transition away from HFCs in stationary cooling appliances, as the associated greenhouse gas reductions are significant.

Competing interests. The authors declare that they have no conflict of interest.

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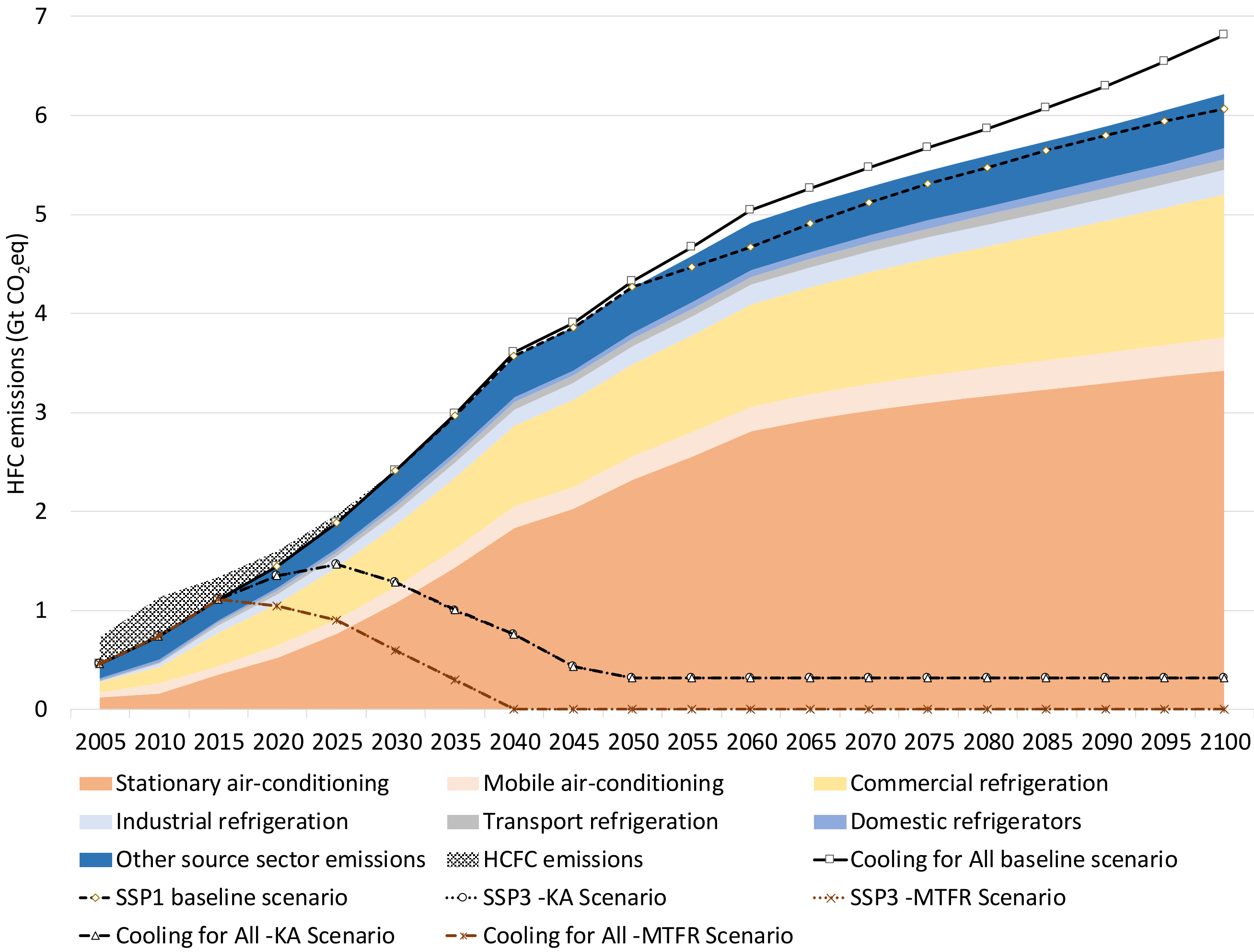

HFC emissions (Gt CO2eq)
7
6
5
4
3
2
1
0
2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100
Stationary air-conditioning
Mobile air-conditioning
Commercial refrigeration
Industrial refrigeration
Transport refrigeration
Domestic refrigerators
Other source sector emissions
HCFC emissions
Cooling for All baseline scenario
SSP1 baseline scenario
SSP3 -KA Scenario
SSP3 -MTFR Scenario
Cooling for All -KA Scenario
Cooling for All -MTFR Scenario

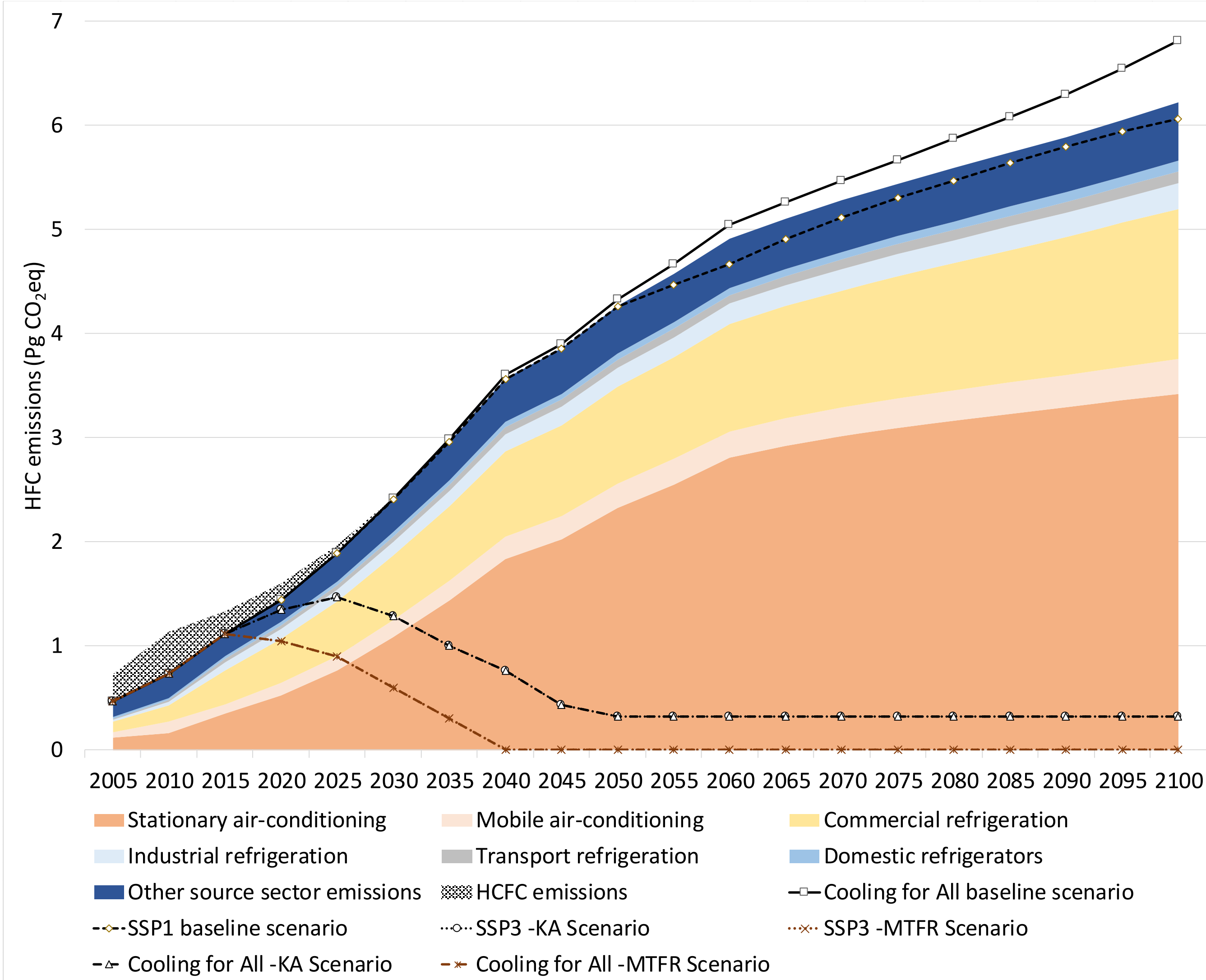
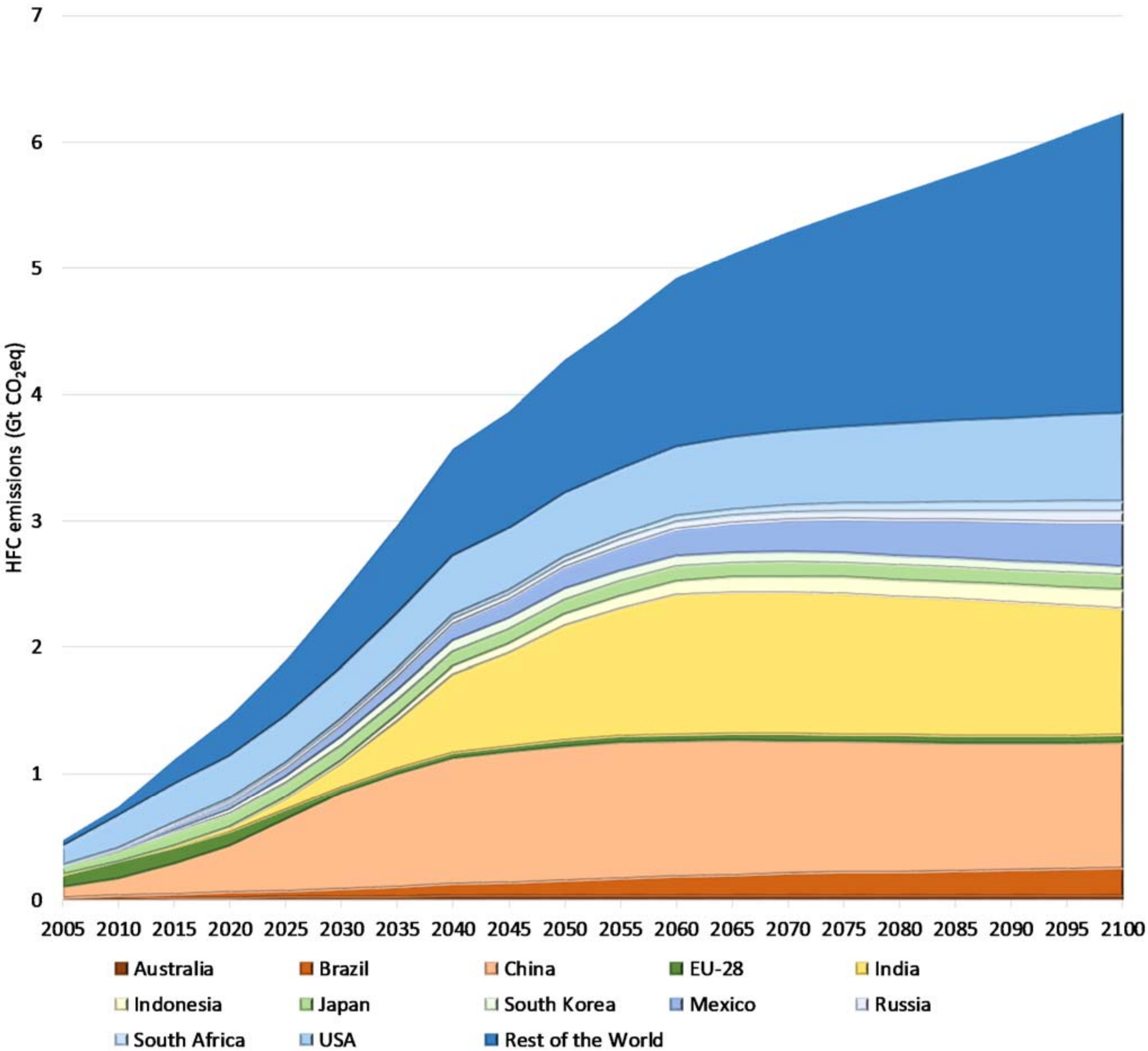


Figure 1: Pre-~~KA~~Kigali SSP3 baseline HFC emissions (with baseline SSP1 and *Cooling for All* shown for comparison) and respective alternative scenarios (~~KA/MTFR).~~Kigali Amendment -KA and Maximum Technically Feasible Reduction -MTFR). Note that *Cooling for All* -KA and *Cooling for All* -MTFR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


HFC emissions (Gt CO_2eq)
0
1
2
3
4
5
6
7
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
Australia
Brazil
China
EU-28
India
Indonesia
Japan
South Korea
Mexico
Russia
South Africa
USA
Rest of the World

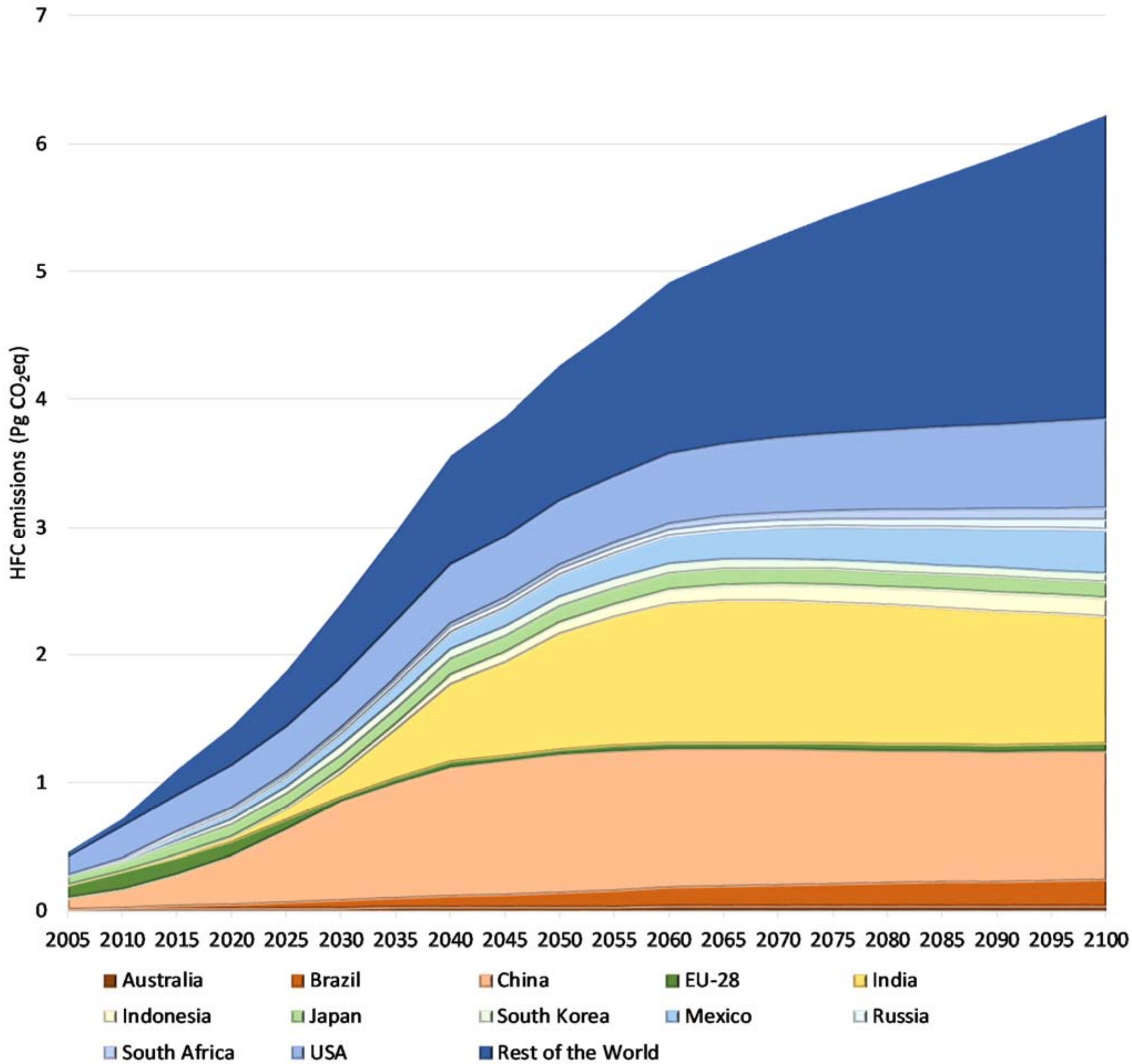
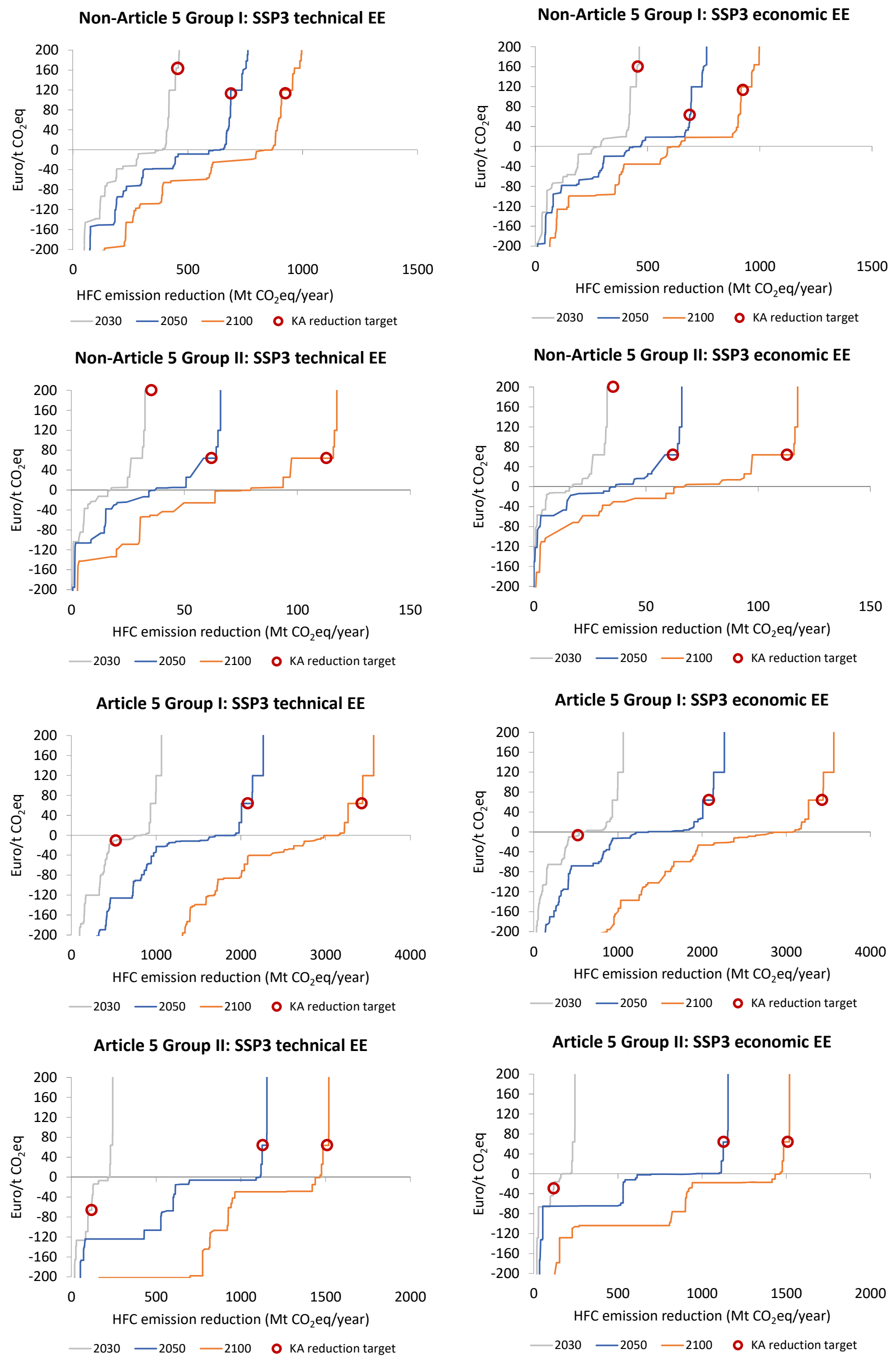


Figure 2: Pre-~~KA~~Kigali SSP3 baseline HFC emissions by regions


Non-Article 5 Group I: SSP3 technical EE
Non-Article 5 Group I: SSP3 economic EE
Non-Article 5 Group II: SSP3 technical EE
Non-Article 5 Group II: SSP3 economic EE
Article 5 Group I: SSP3 technical EE
Article 5 Group I: SSP3 economic EE
Article 5 Group II: SSP3 technical EE
Article 5 Group II: SSP3 economic EE
Euro/t CO_2eq
HFC emission reduction (Mt CO_2eq/year)
2030
2050
2100
KA reduction target

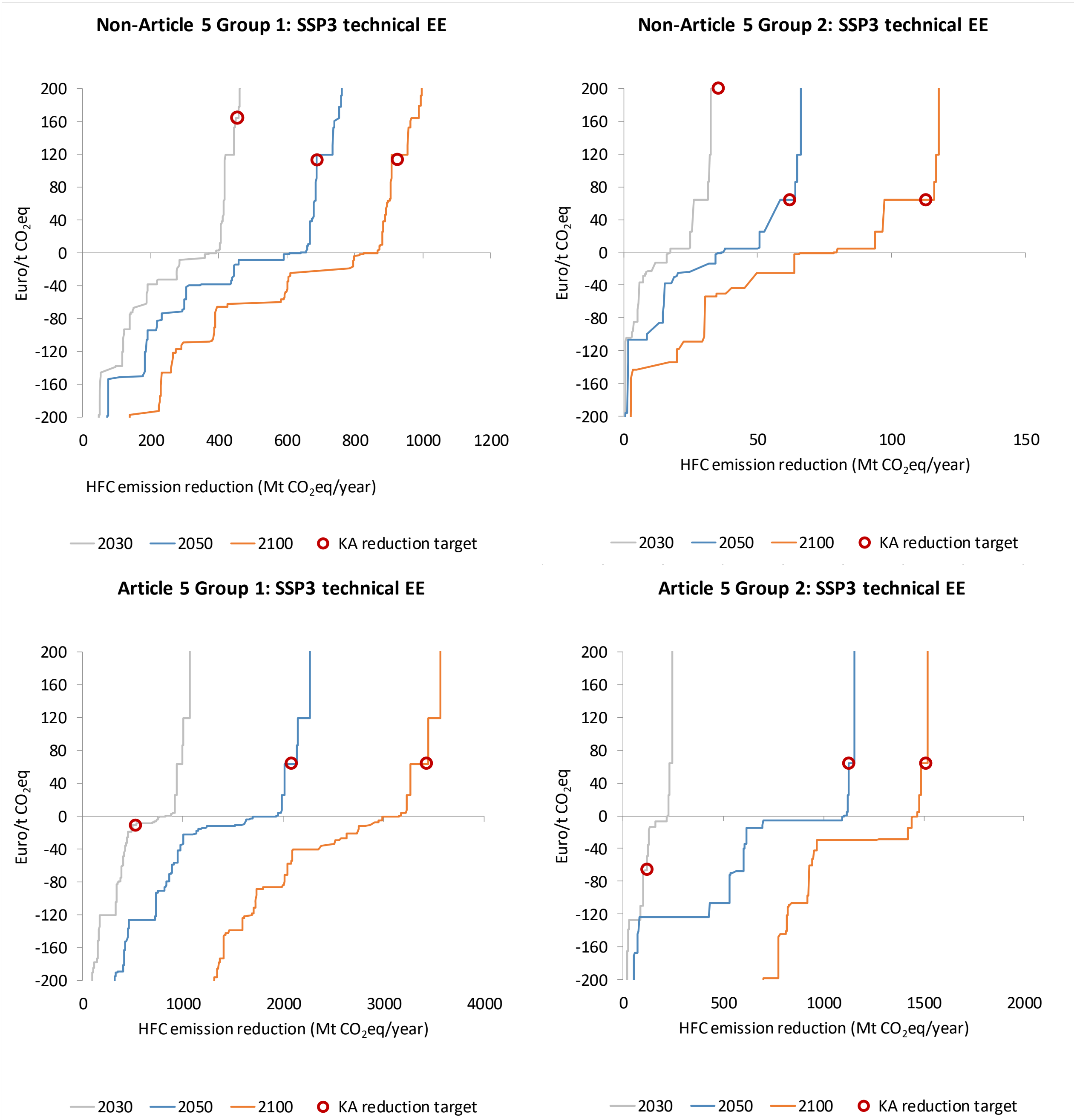
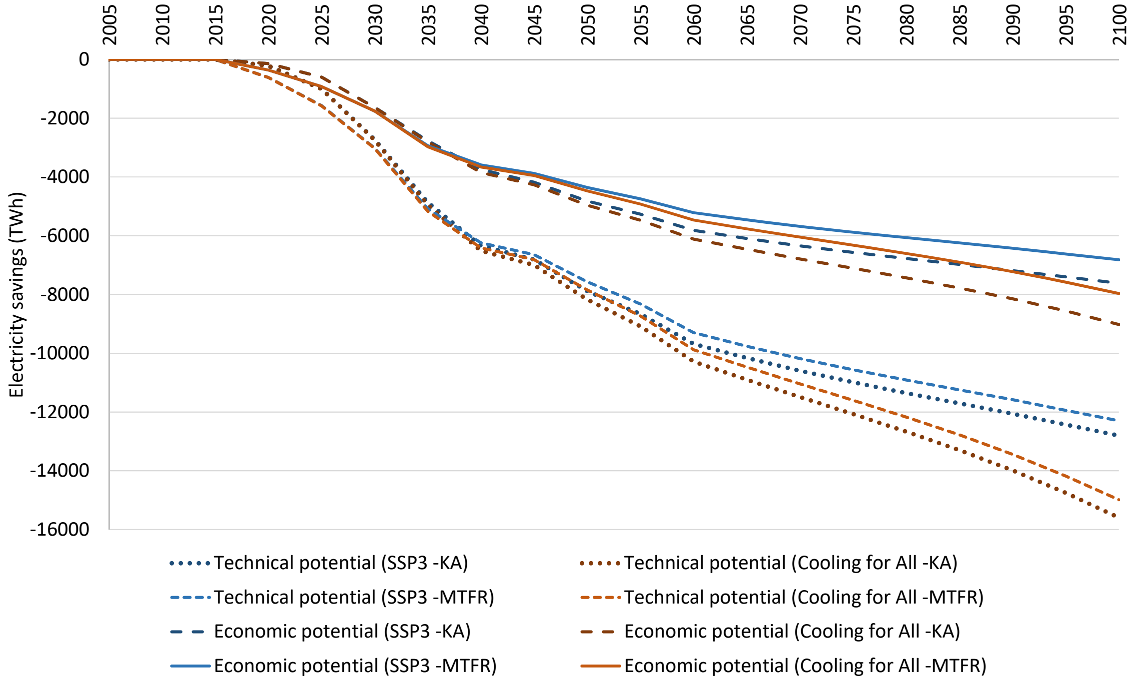


Figure 3: Marginal abatement cost curves (MACCs) starting from a pre-~~KA~~Kigali SSP3 baseline consistent with the IEA-WEO17 New Policies scenario~~) to reduce~~ and reducing HFC emissions by Kigali Amendment (KA) party groups under technical energy efficiency improvements and indicating the KA HFC reduction targets in 2030, 2050 and 2100. ~~Left- and right- side panels represent marginal abatement cost curves assuming "technical" and "economic" energy efficiency improvements, respectively.~~



2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
0
-2000
-4000
-6000
-8000
-10000
-12000
-14000
-16000
Electricity savings (TWh)
Technical potential (SSP3 -KA)
Technical potential (Cooling for All -KA)
Technical potential (SSP3 -MTFR)
Technical potential (Cooling for All -MTFR)
Economic potential (SSP3 -KA)
Economic potential (Cooling for All -KA)
Economic potential (SSP3 -MTFR)
Economic potential (Cooling for All -MTFR)

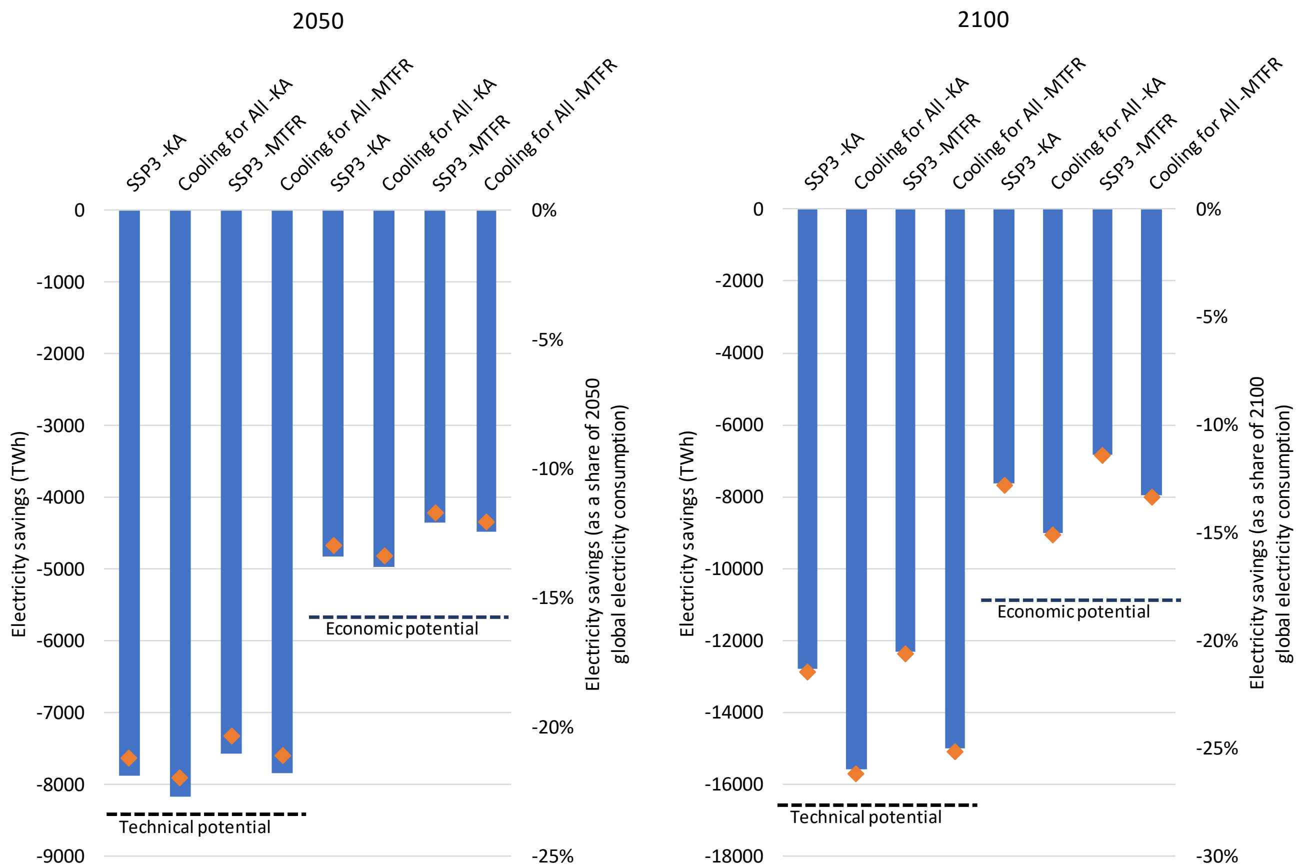
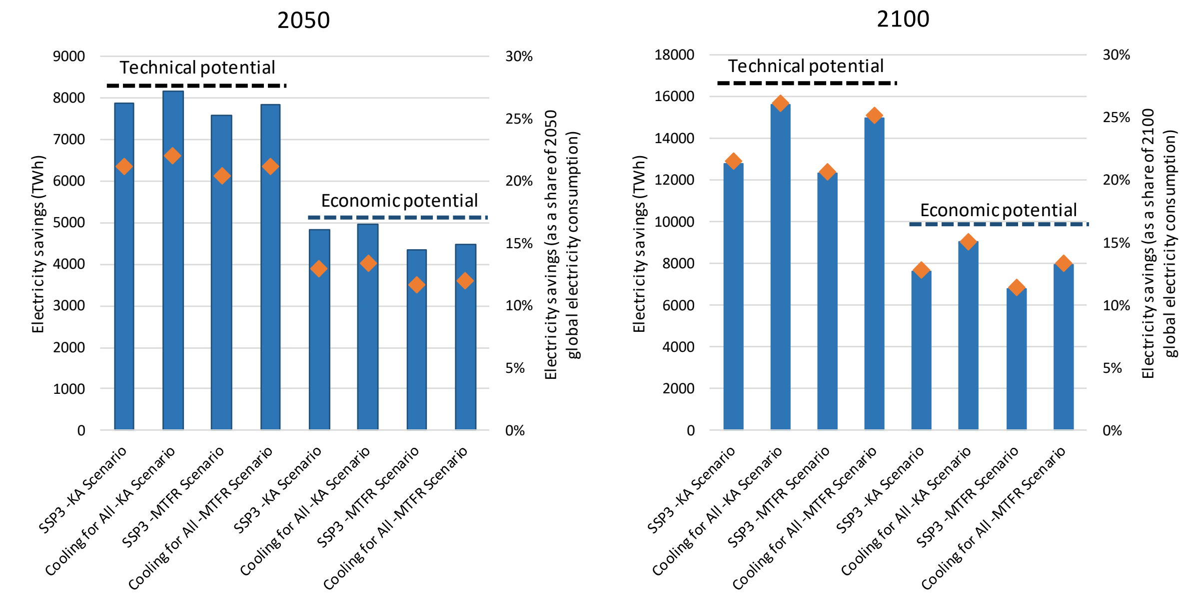
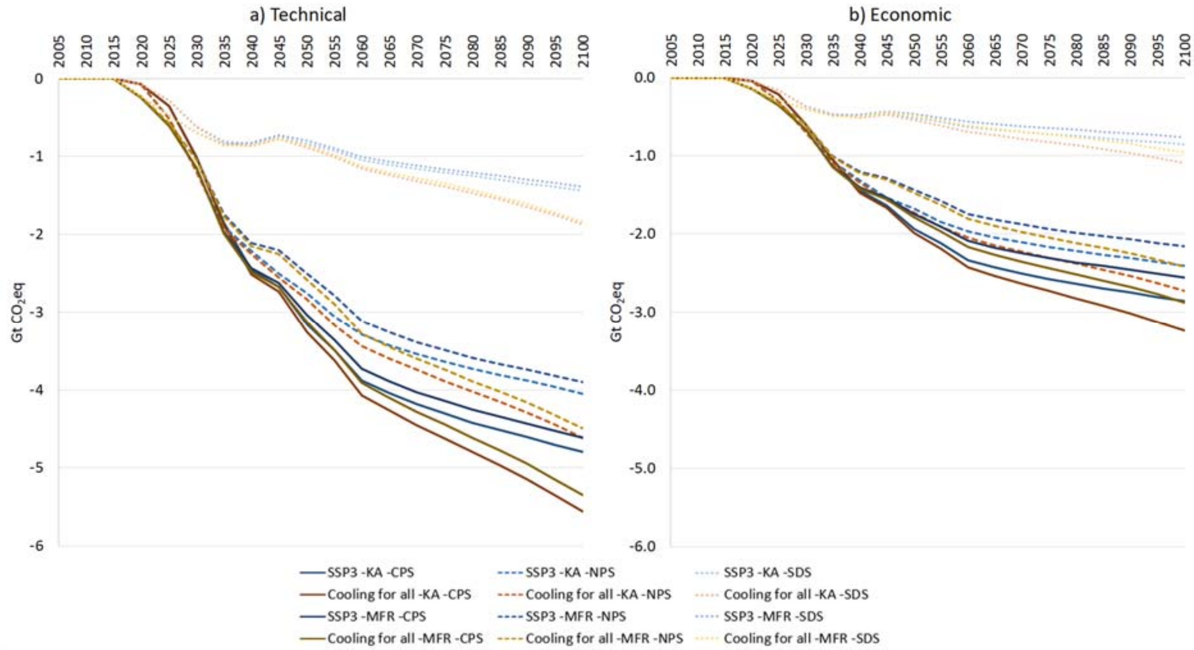


Figure 4: Technical and economic electricity saving (TWh) potentials in HFC reduction scenarios (KA and MTFR) relative pre-KA baselines (SSP3 and *Cooling for All*)



~~Figure 5:~~ **Annual electricity saving potentials when moving from pre-~~KA~~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).**



a) Technical
b) Economic
Gt CO2eq
SSP3 -KA -CPS
Cooling for all -KA -CPS
SSP3 -MFR -CPS
Cooling for all -MFR -CPS
SSP3 -KA -NPS
Cooling for all -KA -NPS
SSP3 -MFR -NPS
Cooling for all -MFR -NPS
SSP3 -KA -SDS
Cooling for all -KA -SDS
SSP3 -MFR -SDS
Cooling for all -MFR -SDS

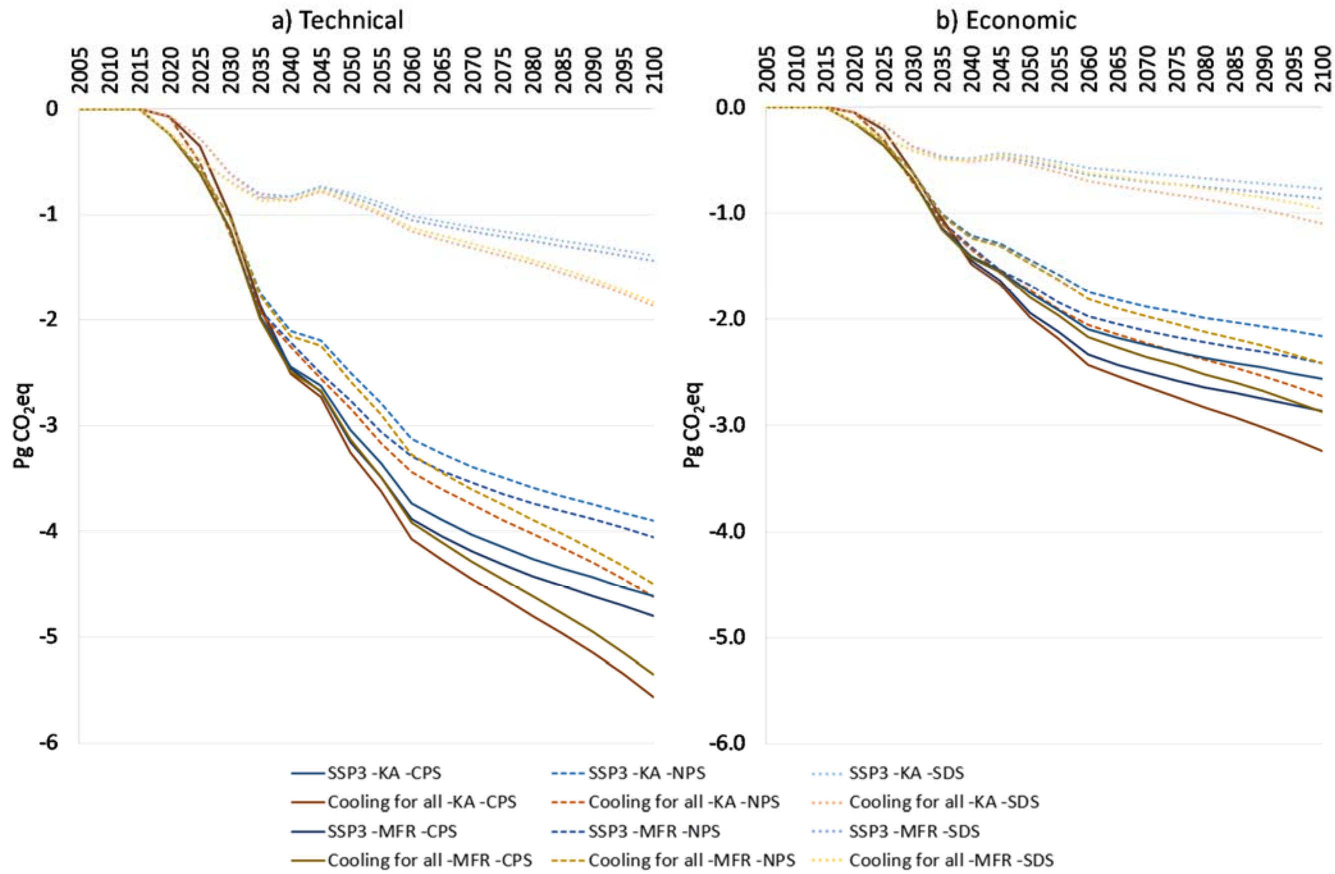
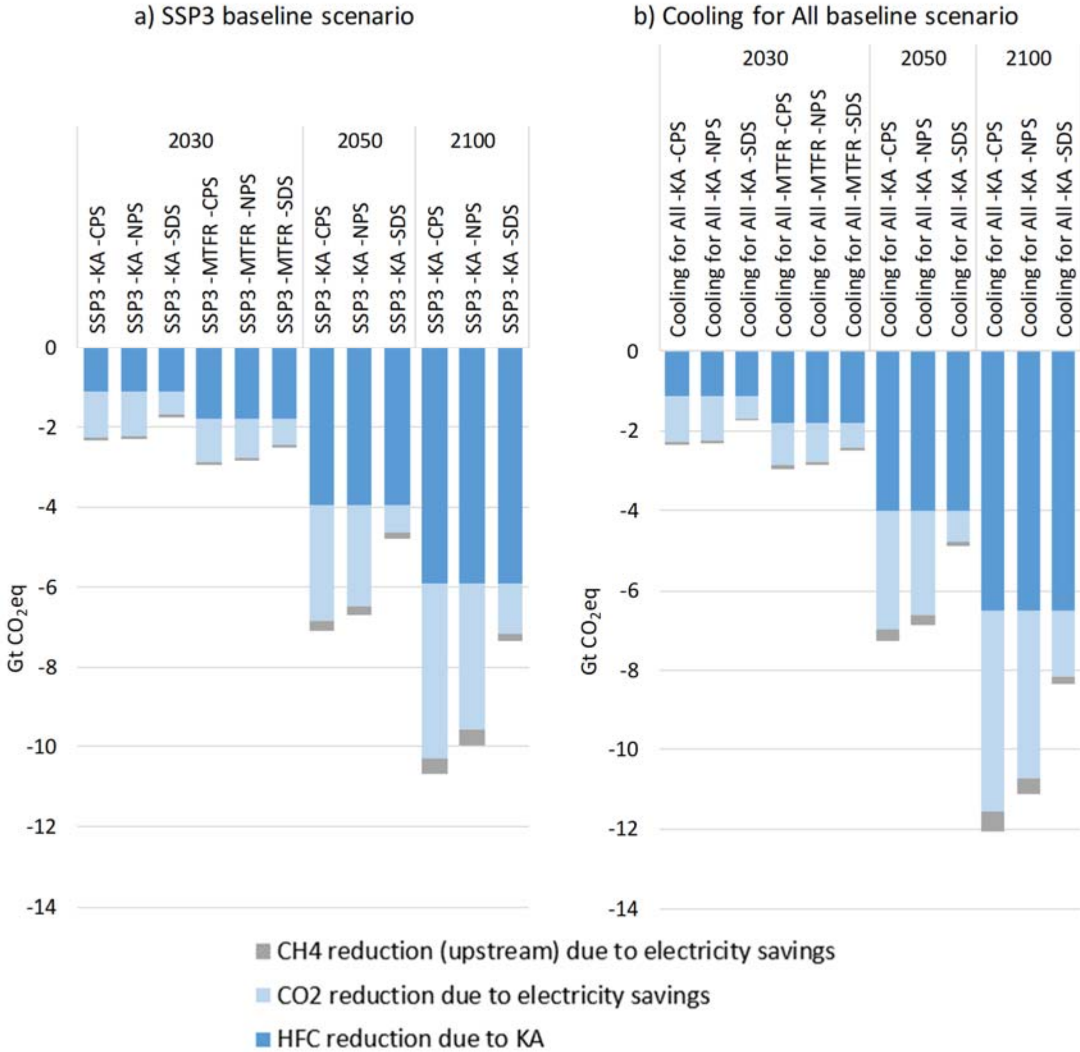


Figure ~~6~~5: Annual ~~GHG~~greenhouse gas emission reductions from electricity savings in the Kigali Amendment (KA) and Maximum Technically Feasible Reduction (MTFR) scenarios relative the pre-~~KA~~Kigali baseline scenarios (SSP3 and *Cooling for All*). Results for technical energy efficiency improvements are shown in Panel a) and for economic energy efficiency improvements in Panel b).



a) SSP3 baseline scenario
2030
2050
2100
SSP3 -KA -CPS
SSP3 -KA -NPS
SSP3 -KA -SDS
SSP3 -MTFR -CPS
SSP3 -MTFR -NPS
SSP3 -MTFR -SDS
SSP3 -KA -CPS
SSP3 -KA -NPS
SSP3 -KA -SDS
SSP3 -KA -CPS
SSP3 -KA -NPS
SSP3 -KA -SDS
Gt CO2eq
0
-2
-4
-6
-8
-10
-12
-14
b) Cooling for All baseline scenario
2030
2050
2100
Cooling for All -KA -CPS
Cooling for All -KA -NPS
Cooling for All -KA -SDS
Cooling for All -MTFR -CPS
Cooling for All -MTFR -NPS
Cooling for All -MTFR -SDS
Cooling for All -KA -CPS
Cooling for All -KA -NPS
Cooling for All -KA -SDS
Cooling for All -KA -CPS
Cooling for All -KA -NPS
Cooling for All -KA -SDS
Gt CO2eq
0
-2
-4
-6
-8
-10
-12
-14
CH4 reduction (upstream) due to electricity savings
CO2 reduction due to electricity savings
HFC reduction due to KA

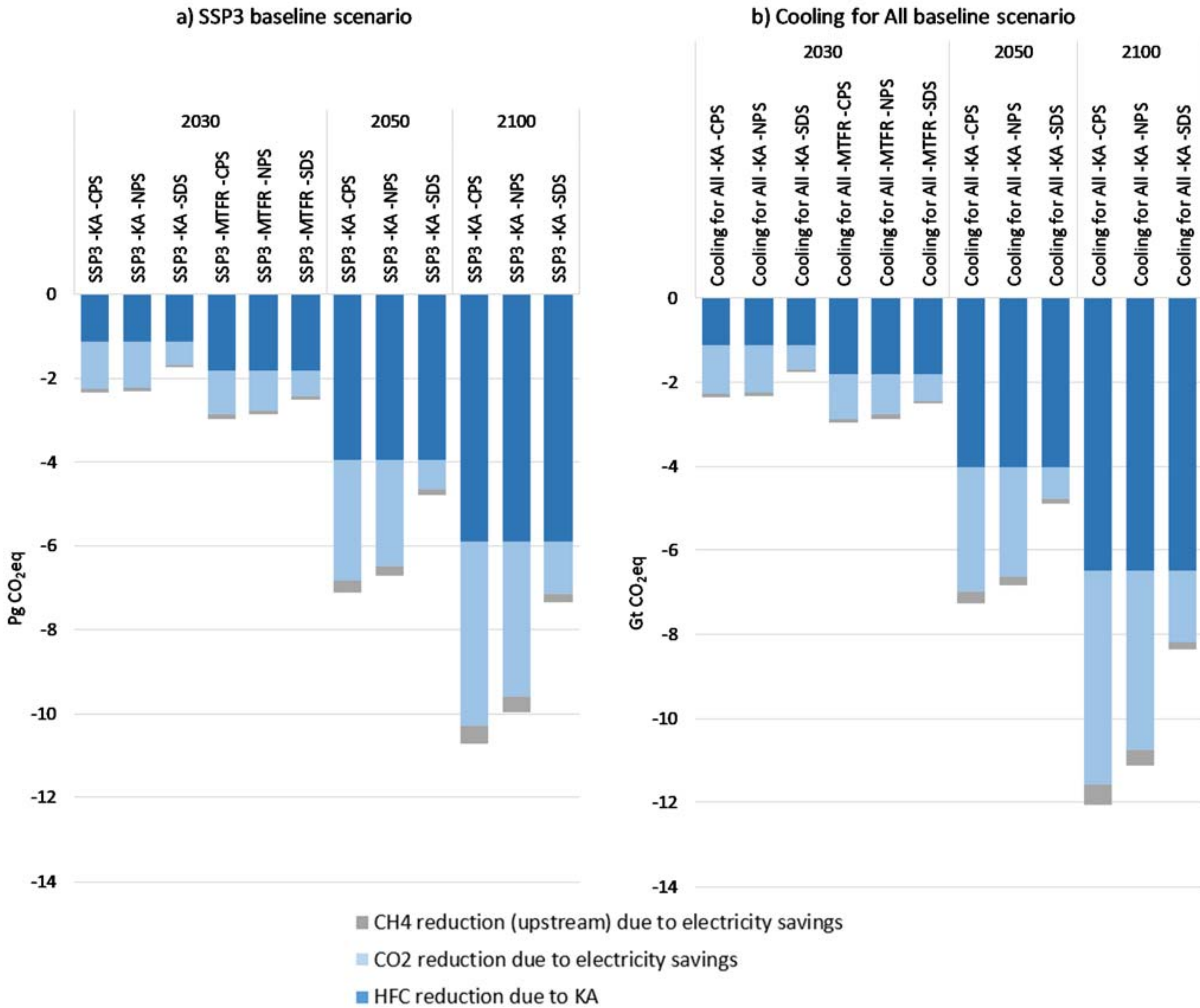
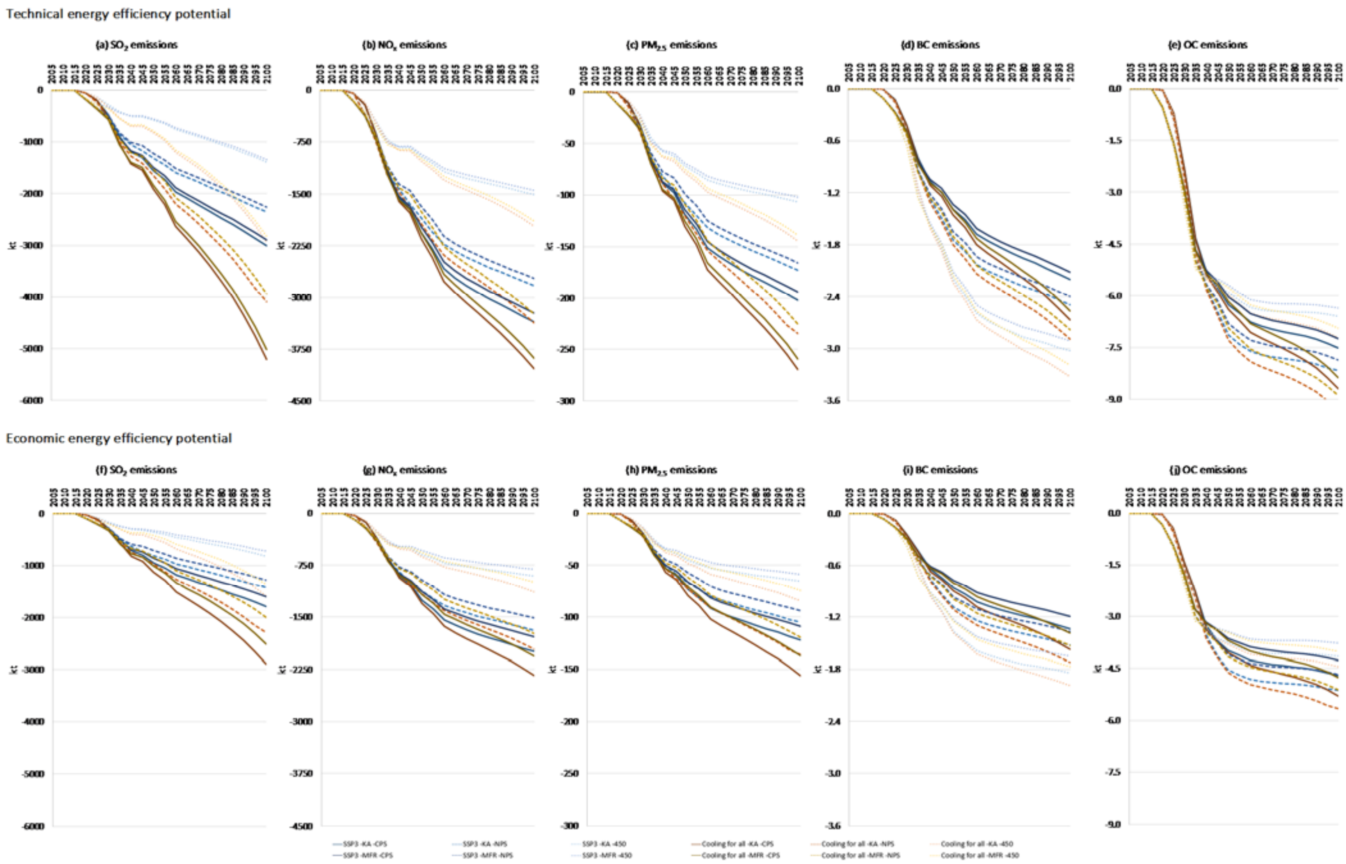
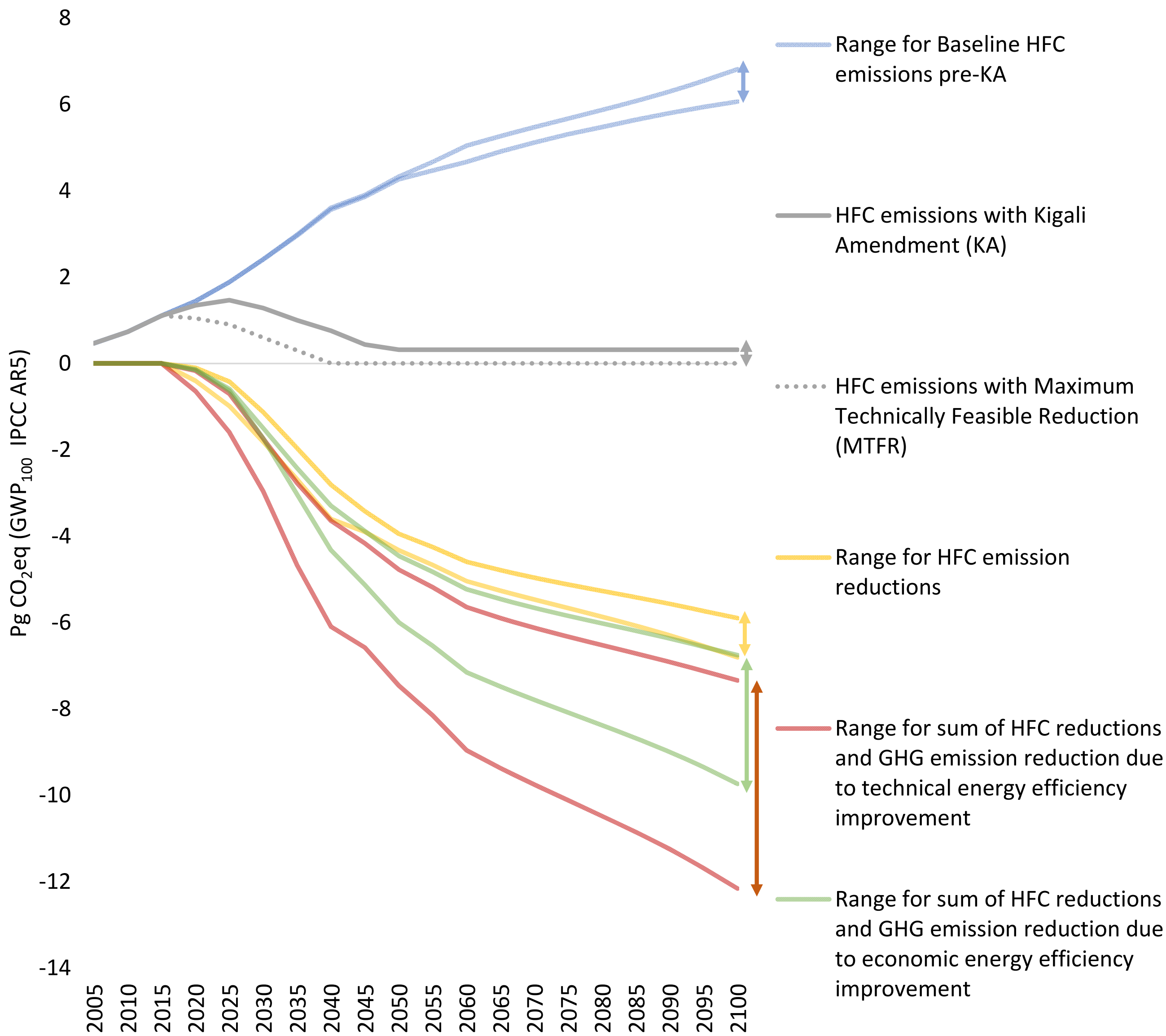


Figure 7: GHG6: Greenhouse gas mitigation (in GtPg CO_2eq) due to enhanced energy efficiency benefits under Kigali amendment (KA) in the alternative scenarios with respect to the a) SSP3 baseline scenario and b) *Cooling for All* baseline scenario. In 2050 and 2100 differences between KA and MTFRMaximum Technically Feasible Reduction (MTFR) scenarios are negligible.


Technical energy efficiency potential
(a) SO_2 emissions
(b) NO_x emissions
(c) $PM_{2.5}$ emissions
(d) BC emissions
(e) OC emissions
Economic energy efficiency potential
(f) SO_2 emissions
(g) NO_x emissions
(h) $PM_{2.5}$ emissions
(i) BC emissions
(j) OC emissions
kt
SSP3 -KA -CPS
SSP3 -MFR -CPS
SSP3 -KA -NPS
SSP3 -MFR -NPS
SSP3 -KA -450
SSP3 -MFR -450
Cooling for all -KA -CPS
Cooling for all -MFR -CPS
Cooling for all -KA -NPS
Cooling for all -MFR -NPS
Cooling for all -KA -450
Cooling for all -MFR -450



940 **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.**

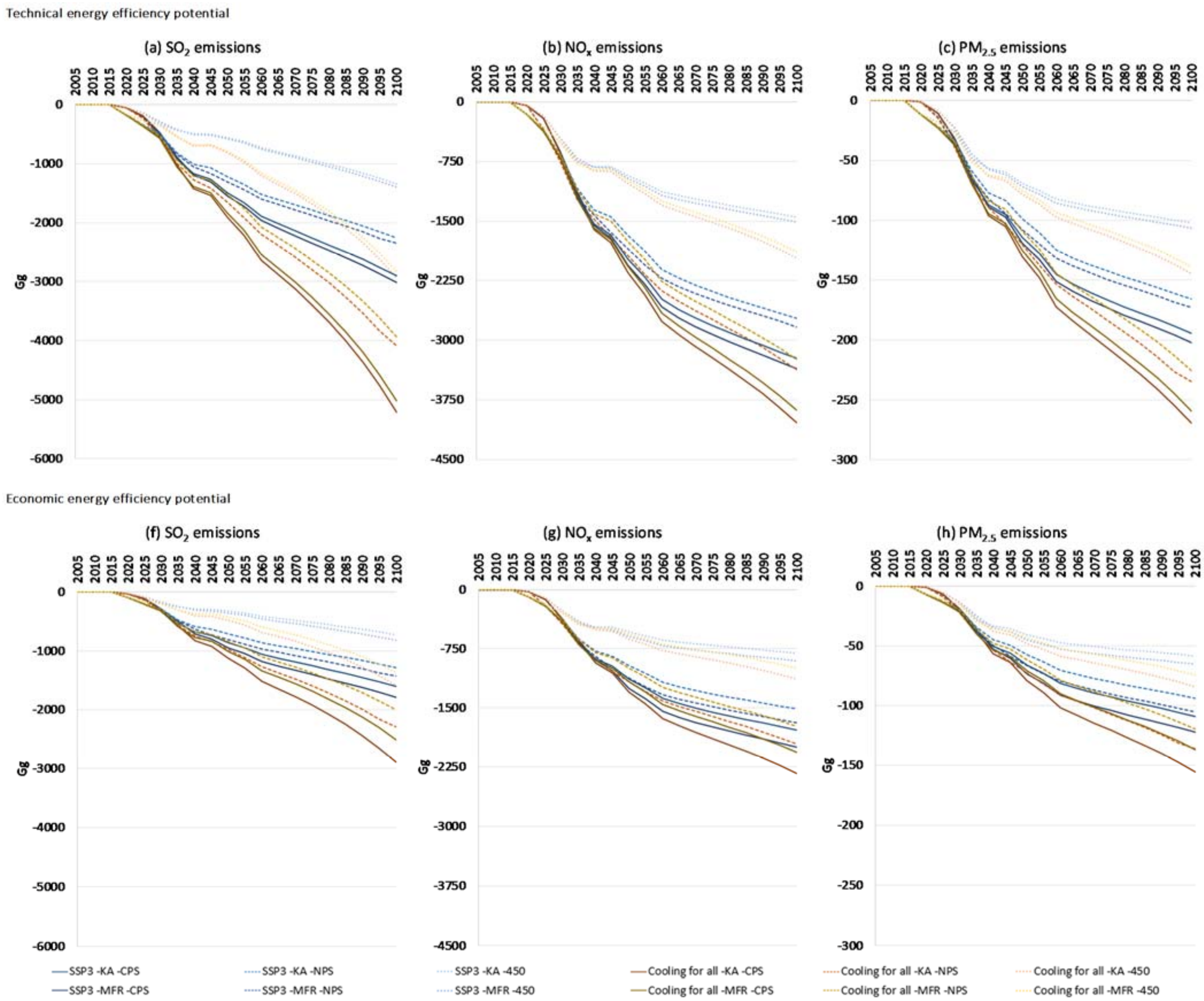


Figure 8: Impacts on air pollutant ~~and SLCP~~ emissions due to electricity savings associated with alternative HFC phase-down ~~paths~~pathways.

Table 1: Overview of the 31 variants of HFC/co-benefits emission scenarios analysed in this study (CPS refers to the Current Policies Scenario, NPS to New Policies Scenario, and SDS to Sustainable Development scenario of IEA-WEO 2017).

		Alternative emission reduction scenarios													
	Baseline	a) Kigali Amendment (*KA*)	b) KA with High Energy Efficiency (*KA-EE*)						c) Maximum Technically Feasible Reduction (*MTFR*)	d) MTFR with High Energy Efficiency (*MTFR-EE*)					
			Technical EE potential			Economic EE potential				Technical EE potential			Economic EE potential		
			CPS	NPS	SDS	CPS	NPS	SDS		CPS	NPS	SDS	CPS	NPS	SDS
Baseline –SSP1	~~X~~✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Baseline –SSP3	~~X~~✓	~~X~~✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓
Cooling for All	~~X~~✓	~~X~~✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓	~~X~~ ✓

Table 2. Sector specific ~~Low-GWP~~alternative options for high-GWP HFCs considered in the GAINS model

Sector	Low-GWP Alternatives
Aerosol	ALT_HC (e.g. HC-290), ALT_HFO (e.g. HFO-1234ze), ALT_HFC (e.g. HFC-152a)
Commercial refrigeration	ALT_HC (e.g. HC-290), ALT_HFO (e.g. HFO-1234yf), ALT_CO_2, ALT_HFC (e.g. HFC-32)
Domestic refrigerators	ALT_HC (e.g. HC-600a)
Fire-extinguishers	FK (e.g. FK-5-1-12)
Foam	ALT_HC (e.g. iso-pentane), ALT_HFO (e.g. HFO-1234ze), ALT_HFC (e.g. HFC-152a), ALT_CO_2
Ground source heat pumps	ALT_HC (e.g. HC-290), ALT_HFO (e.g. HFO-1234yf), ALT_CO_2, ALT_HFC (e.g. HFC-32)
Industrial refrigeration	ALT_NH_3, ALT_CO_2
Mobile air-conditioning	ALT_HFO (e.g. HFO-1234yf), ALT_CO_2
Solvents*	Iso-paraffin/siloxane (KC-6)
Stationary air-conditioning	ALT_HC (e.g. HC-290), ALT_HFO (e.g. HFO-1234yf), ALT_HFC (e.g. HFC-32), ALT_CO_2
Transport refrigeration	ALT_HC (e.g. HC-290, HC-1270), ALT_CO_2, ALT_HFC (e.g. HFC-32)

*GAINS also consider a complete ban on HFC based solvents as a control option.

Table 3: Pre-KAKigali baseline HFC emissions per capita in residential air-conditioning and domestic refrigerators under the SSP3 and *Cooling for All* scenarios

Party group	Scenario	Sector	HFC emissions per capita (kg/capita)	
			2050	**2100**
Article 5	SSP3 baseline scenario	Room air-conditioners	107.9	144.3
		Domestic refrigerators	5.9	9.0
	Cooling for All baseline scenario	Room air-conditioners	114.9	196.7
		Domestic refrigerators	6.7	9.4
Non-Article 5	SSP3 baseline scenario	Room air-conditioners	88.6	139.8
		Domestic refrigerators	3.9	5.3
	Cooling for All baseline scenario	Room air-conditioners	88.6	139.8
		Domestic refrigerators	3.9	5.3

Table 4: Cumulative HFC emissions in the pre-~~KA~~Kigali Baseline and corresponding ~~KA~~Kigali Amendment (KA) and Maximum Technically Feasible Reduction (MTFR) scenarios by KA party groups and over the entire period 2018 to 2100.

Scenarios	Cumulative HFC emissions (~~Gt~~Pg CO_2eq)				
	Non-Art.5 (Group–I)	Non-Art.5 (Group–II)	Art. 5 (Group–I)	Art. 5 (Group–II)	Global
pre-KA SSP3 baseline	66.8	6.1	199.7	90.6	363.2
● *Under KA compliance*	10.5	0.6	30.5	6.6	48.2
● *Under MTFR*	4.2	0.2	7.2	1.3	12.9
pre-KA *Cooling for All* baseline	66.8	6.2	212.7	91.9	377.5
● *Under KA compliance*	10.5	0.6	30.6	6.6	48.2
● *Under MTFR*	4.2	0.2	7.3	1.3	13.0
pre-KA SSP1 baseline	75.5	5.7	197.3	76.8	355.3

Table 5: Cumulative reductions in ~~GHG~~greenhouse gas emissions 2018-2100 due to electricity-savings induced by HFC phase-down when assuming technical and economic energy efficiency improvement potentials, by Kigali Amendment party groups.

Scenarios	GHG reductions due to KA and enhanced energy efficiency (~~Gt~~Pg CO_2eq)				
	Non-A5 Group-I	Non-A5 Group-II	A5 Group-I	A5 Group-II	Global
Technical energy efficiency potential					
SSP3 -KA –CPS	98.8	12.2	329.5	190.4	631.0
SSP3 -KA –NPS	95.2	6.7	299.2	183.5	584.6
SSP3 -KA –SDS	71.9	6.3	243.5	119.8	441.4
Cooling for All -KA –CPS	98.8	12.4	359.3	193.9	664.4
Cooling for All -KA –NPS	95.2	6.8	324.7	186.7	613.4
Cooling for All -KA –SDS	71.9	6.4	266.0	122.4	466.7
SSP3 -MTFR –CPS	97.4	11.8	327.5	188.2	625.0
SSP3 -MTFR –NPS	94.0	6.1	298.0	181.6	579.6
SSP3 -MTFR –SDS	71.6	6.1	243.6	119.7	441.0
Cooling for All -MTFR –CPS	97.4	6.2	356.7	191.6	651.9
Cooling for All -MTFR –NPS	94.0	6.2	324.2	184.9	609.2
Cooling for All -MTFR –SDS	71.6	6.2	266.5	122.4	466.8
Economic energy efficiency potential					
SSP3 -KA –CPS	86.2	7.0	278.4	149.1	520.7
SSP3 -KA –NPS	84.0	7.0	259.9	145.0	495.9
SSP3 -KA –SDS	69.9	6.7	226.2	107.7	410.5
Cooling for All -KA –CPS	86.2	7.0	286.8	150.1	530.2
Cooling for All -KA –NPS	84.0	7.0	266.8	146.1	503.9
Cooling for All -KA –SDS	69.9	6.7	231.5	108.5	416.5
SSP3 -MTFR –CPS	84.8	7.0	272.8	143.4	508.0
SSP3 -MTFR –NPS	82.8	6.9	255.9	139.8	485.4
SSP3 -MTFR –SDS	69.6	6.6	224.8	106.5	407.5
Cooling for All -MTFR –CPS	84.8	7.0	279.7	144.3	515.9
Cooling for All -MTFR –NPS	82.8	6.9	261.5	140.7	492.0
Cooling for All -MTFR –SDS	69.6	6.6	229.1	107.1	412.5

Electricity savings and greenhouse gas emission reductions from global phase-down of hydrofluorocarbons

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S1: Current legislation on HFC control considered in the Baselines

To estimate hydrofluorocarbon (HFC) emissions in the baseline scenarios, we take into account the effects on emissions from implementation of existing legislations to control HFC emissions at the regional or national level. The European Union (EU) first legislated to control emissions of HFCs in 2006 (Höglund-Isaksson et al., 2012; Höglund-Isaksson et al., 2013), adopting a regulation on emissions and a directive on mobile air-conditioning (EU, 2006). Regulation 842/2006 on certain fluorinated greenhouse gases (GHGs) aimed only at containment, through measures such as control of leaks, proper servicing of equipment and recovery of the gases at the end of the equipment's life. In May 2014, this was replaced by the much more ambitious Regulation 517/2014 on fluorinated GHGs (the F-Gas Regulation[1]), which entered into force on 1st January 2015. It is aimed at achieving a reduction in sales of HFCs on the EU market by 79 percent (GWP-weighted) from 2009–12 levels by 2030 (EU, 2014), with interim reduction steps starting in 2015 and applying roughly every three years. In addition, HFCs are banned outright in some categories of new equipment where alternatives are readily available.

Apart from the EU, Japan, the USA, Australia, Norway, and Switzerland have also implemented national regulations to limit the use of high-GWP HFCs. The USA has already implemented incentive credits for use of low-GWP refrigerants in support of greenhouse gas emission standards for light duty vehicles and removed certain high-GWP HFCs from the Significant New Alternatives Policy (SNAP) list of allowable technologies for specific sectors in 2015 (US EPA, 2015). Although recently legally challenged (Reilly, 2017), the changes to the SNAP list ban the use of many high-GWP HFCs in, for example, commercial refrigeration applications, such as supermarket systems and vending machines, beginning during the period 2016–2020 and in mobile air-conditioning from model year 2021. The implementation of the new SNAP list is estimated to reduce baseline USA HFC emissions by 0.18–0.24 ~~Gt~~Pg CO_2eq per year (about 43%) by 2050 (Velders et al., 2015). In Japan, the Fluorocarbons Recovery and Destruction Law was amended and became effective on 1st April 2015 as the *Act on Rational Use and Proper Management of Fluorocarbons* (Fluorocarbon Emission Control Law) (METI, 2015). Among other requirements, the Act requires entities manufacturing and importing air-conditioning and refrigeration units to transition to either fluorocarbon-free refrigerants or to low global warming fluorocarbons by certain target years.

For developing countries, several studies discuss the impact of the Clean Development Mechanism (CDM) projects on HFC-23 emissions from HCFC-22 production for emissive and feedstock applications (Wara, 2007; Miller et al., 2010; Montzka et al., 2010; Miller and Kuijpers, 2011; Schneider, 2011). HFC-23 emissions from HCFC-22 production are assumed to be controlled in most developing countries due to CDM (Fenhann, 2014), except China where 36% of HCFC-22 production is controlled (Feng et al., 2012). The Chinese production capacity of HCFC-22 accounts for 78% of the global HCFC production (UNEP, 2014). HCFC-22 is a major source of HFC-23 emissions, which is a strong greenhouse gas with GWP_{100} of 14,800 times that of CO_2 (IPCC, 2007).

In its Intended Nationally Determined Contribution (INDC) submitted in June 2015, China reiterated its commitment under the Montreal Protocol to achieve effective control on emissions of HFC-23 by 2020. In 2015, the Chinese National Development and Reform Commission (NDRC) announced that it plans to achieve abatement of all HFC-23 emissions by 2019 (NDRC, 2015). This would imply installing destruction technology in all plants currently not covered by CDM and ensuring that the destruction technology on plants covered under CDM is being operated and maintained. In line with this information, we assume in recent updates of the GAINS model that all HCFC-22 production facilities in China will be fully controlled from 2020 onwards. It is observed that except for China other developing countries do not make HFC specific emission reduction commitments in the INDCs. In the 28th Meeting of the Parties to the Montreal Protocol in October 2016 in Kigali, the Indian government presented a domestic legislation that mandates control of trifluoromethane (HFC-23) emissions. At present, all HCFC-22 production facilities in India are fully controlled under the Clean Development Mechanism (CDM) and we assume the control on all Indian facilities stays operational and will be maintained in the future.

S2: The Kigali Amendment to the Montreal Protocol

The Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer entered into force on 1st January 2019, following ratification by 65 countries[1]. KA sets targets for the phase-down of HFCs consumption for four different Party groups. The first group primarily includes 136 developing countries that make up all Article 5 countries as specified under the Montreal Protocol with the exception of Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, and the United Arab Emirates (UAE). These ten countries are characterized by high ambient air temperatures and make up a second and separate group of Article 5 countries. Countries specified as non-Article 5 countries under the Montreal Protocol are primarily developed countries and under the Kigali Amendment divided into two separate groups with 45 countries in a first group and with the five countries Belarus, the Russian Federation, Kazakhstan, Tajikistan and Uzbekistan forming a separate second group. Table 1 presents the baseline years and HFC phase-down schedule of Article 5 and non-Article 5 Parties. We will hereafter refer to these four Party groups as Article 5 Group ~~I~~1, Article 5 Group ~~II~~2, non-Article 5 Group ~~I~~1, and non-Article 5 Group ~~II~~2.

[1] The Parties to the Montreal Protocol agreed that the Kigali amendment to the Montreal Protocol would *enter into force* on 1 January 2019, provided that at least 20 Parties had ratified it.

Table S1: Baseline and HFC phase-down schedule of Article-5 and non- Article-5 Parties

	Article 5[*] (A5) Parties: Group ~~I~~1[**]		**Article 5 (A5) Parties: Group ~~II~~2[+]**	
Baseline Years	2020, 2021 & 2022		2024, 2025 & 2026	
Baseline calculation	Average production /consumption of **HFCs** in 2020, 2021, and 2022 *plus* **65%** of **HCFC** baseline production/consumption		Average production /consumption of **HFCs** in 2024, 2025, and 2026 *plus* **65%** of **HCFC** baseline production/consumption	
Reduction steps Freeze	2024		2028	
Step 1	2029	10%	2032	10%
Step 2	2035	30%	2037	20%
Step 3	2040	50%	2042	30%
Step 4	2045	80%	2047	85%
	Non-Article 5 (non-A5): Group ~~I~~1		**Non-Article 5 (non-A5): Group ~~II~~2[++]**	
Baseline Years	2011, 2012 & 2013		2011, 2012 & 2013	
Baseline Calculation	Average production /consumption of **HFCs** in 2011, 2012 & 2013 *plus* **15%** of **HCFC** baseline production/consumption		Average production /consumption of **HFCs** in 2011, 2012 & 2013 *plus* **25%** of **HCFC** baseline production/consumption	
Reduction steps Step 1	2019	10%	2020	5%
Step 2	2024	40%	2025	35%
Step 3	2029	70%	2029	70%
Step 4	2034	80%	2034	80%
Step 5	2036	85%	2036	85%

[*] 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.

[**]Group 1: Article 5 parties not part of Group 2

[+] Group 2: Bahrain, India, the Islamic Republic of Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia and the United Arab Emirates

[++] For Belarus, Russian Federation, Kazakhstan, Tajikistan, Uzbekistan, 25% HCFC component of baseline and different initial two steps (1) 5% reduction in 2020 and (2) 35% reduction in 2025

Source: UNEP (2016)

Table S2: Technical and economic energy efficiency (EE) potential of cooling technologies in baseline and with low-GWP alternatives

Countries	Year	EE due to systems improvements and low-GWP refrigerant (%)					
		HCFC-22/HFC-410A		HC-290		HFC-32/ HFOs	
		Economic	Technical	Economic	Technical	Economic	Technical
1. Mini-split air-conditioners (1.5 ton base-unit size)							
Brazil	2014	30%	70%	36%	73%	35%	72%
Chile	2014	30%	70%	36%	73%	35%	72%
China	2014	30%	70%	36%	73%	35%	72%
Colombia	2014	30%	70%	36%	73%	35%	72%
Egypt	2014	30%	70%	36%	73%	35%	72%
India	2014	30%	70%	36%	73%	35%	72%
Indonesia	2014	30%	70%	36%	73%	35%	72%
Mexico	2014	30%	70%	36%	73%	35%	72%
Pakistan	2014	30%	70%	36%	73%	35%	72%
Saudi Arabia	2014	30%	70%	36%	73%	35%	72%
Thailand	2014	30%	70%	36%	73%	35%	72%
UAE	2014	30%	70%	36%	73%	35%	72%
Vietnam	2014	30%	70%	36%	73%	35%	72%
2. Packaged air-conditioners (Rooftop units 10 ton AC)							
Asia	2015	31%	49%			37%	53%
North America	2015	31%	49%			37%	53%
Europe	2015	31%	49%			37%	53%
Rest of World	2015	31%	49%			37%	53%
3. VRF/ Ducted air-conditioners (10 ton HP)							
Asia	2015	15%	37%			21%	41%
North America	2015	15%	37%			21%	41%
Europe	2015	15%	37%			21%	41%
Rest of World	2015	15%	37%			21%	41%
4. Chillers, air cooled (Small, <300 tons - 500kW, 143 tons)+							
Asia	~2012-2017	29%	38%			32%	41%
North America	~2012-2017	22%	32%			25%	35%
Europe	~2012-2017	33%	42%			36%	44%
Rest of World	~2012-2017	12%	23%			15%	26%
5. Chillers, air cooled (Large, >= 300 tons - 1500kW, 429 ton) +							
Asia	~2012-2017	30%	38%			33%	41%
North America	~2012-2017	23%	32%			26%	35%
Europe	~2012-2017	35%	42%			37%	44%
Rest of World	~2012-2017	13%	23%			17%	26%

Countries	Year	EE due to systems improvements and low-GWP refrigerant (%)					
		HCFC-22/HFC-410A		HC-290/HC-600a		HFC-32/ HFOs	
		Economic	Technical	Economic	Technical	Economic	Technical
6. Chillers, water cooled (Small, <300 tons - 500kW, 143 tons) +							
Asia	~2012-2017	31%	51%			34%	53%
North America	~2012-2017	18%	41%			21%	44%
Europe	~2012-2017	50%	64%			52%	66%
Rest of World	~2012-2017	25%	46%			28%	49%
7. Chillers, water cooled (Large, >= 300 tons - 1500kW, 429 ton) +							
Asia	~2012-2017	36%	57%			39%	59%
North America	~2012-2017	13%	41%			17%	44%
Europe	~2012-2017	45%	63%			48%	65%
Rest of World	~2012-2017	26%	50%			29%	52%
8. Remote display cabinet - Chilled, multi-deck (RVC2) ++							
Asia	2014	69%	75%	68%	74%		
North America	2014	53%	63%	51%	61%		
Europe	2014	13%	30%	8%	26%		
Rest of World	2014	35%	48%	32%	45%		
9. Remote display cabinet - Frozen, open, island (RHF4) ++							
Asia	2014	23%	23%	19%	19%		
North America	2014	31%	31%	27%	27%		
Europe	2014	17%	17%	13%	13%		
Rest of World	2014	42%	42%	39%	39%		
10. Integral display cabinet - Chilled, multi-deck (IVC2) ++							
Asia	2014	66%	77%	64%	76%		
North America	2014	48%	65%	45%	64%		
Europe	2014	30%	53%	26%	51%		
Rest of World	2014	30%	54%	27%	51%		
11. Integral display cabinet - Chilled, glass door (IVC4) ++							
Asia	2014	15%	30%	11%	26%		
North America	2014	15%	30%	11%	26%		
Europe	2014	15%	30%	11%	26%		
Rest of World	2014	15%	30%	11%	26%		
12. Integral display cabinet - Frozen, open, island (IHF4) ++							
Asia	2014	41%	41%	37%	38%		
North America	2014	47%	47%	44%	45%		
Europe	2014	24%	25%	20%	21%		
Rest of World	2014	56%	56%	53%	54%		

Countries	Year	EE due to systems improvements and low-GWP refrigerant (%)					
		HCFC-22/HFC-410A		HC-290		HFC-32/ HFOs	
		Economic	Technical	Economic	Technical	Economic	Technical
13. Integral display cabinet - Frozen, glass lid, island (IHF6) ++							
Asia	2014	32%	34%	29%	31%		
North America	2014	39%	41%	36%	38%		
Europe	2014	13%	16%	9%	12%		
Rest of World	2014	41%	43%	38%	40%		

Countries	Year	EE due to systems improvements and low-GWP refrigerant (%)					
		HCFC-22/HFC-410A		HC-290/HC-600a		HFC-32/ HFOs	
		Economic	Technical	Economic	Technical	Economic	Technical
14. Domestic refrigerators/freezers (Average size)+++							
Asia	2015	16%	60%	22%	63%		
North America	2015	22%	47%	28%	51%		
Europe	2015	13%	53%	19%	56%		
Rest of World	2015	15%	57%	21%	60%		
15. Beverage vending machines (500 bottle/unit capacity) +++							
Asia	2015	44%	58%	48%	61%		
North America	2015	34%	55%	39%	58%		
Europe	2015	44%	58%	48%	61%		
Rest of World	2015	19%	59%	25%	62%		

RID: Remote and integral displays
+HFO as an alternative low-GWP refrigerant
++CO_2 as an alternative low-GWP refrigerant
+++HC-600a as an alternative low-GWP refrigerant
Source: (DOE, 2011; IEA-4E, 2012a; IEA-4E, 2012b; CLASP, 2013; CLASP, 2014; IEA-4E, 2014; IEA-4E, 2015; Shah et al., 2015; Rosenquist, 2016; UNEP, 2017; DOE, 2018; DOE-FEMP, 2018)

Table S3: Annual technical/economic electricity saving potentials in HFC reduction scenarios relative respective pre-KA baseline scenarios

Year	KA Groups	Technical electricity savings (TWh)				Economic electricity savings (TWh)			
		SSP3 - KA	***Cooling for All - KA***	**SSP3 - MTFR**	***Cooling for All – MTFR***	**SSP3 – KA**	***Cooling for All - KA***	**(SSP3 - MTFR)**	**(*Cooling for All - MTFR*)**
2030	Non-A5 (Group-I)	806	806	767	767	491	491	455	455
	Non-A5 (Group-II)	25	25	25	25	16	16	16	16
	A5 (Group-I)	1452	1464	1708	1717	861	865	993	996
	A5 (Group-II)	449	453	518	521	260	262	290	291
	Global	2732	2748	3018	3030	1628	1634	1754	1759
2050	Non-A5 (Group-I)	1304	1304	1238	1238	795	795	734	734
	Non-A5 (Group-II)	58	59	56	57	37	38	35	35
	A5 (Group-I)	4017	4272	3868	4114	2474	2601	2239	2343
	A5 (Group-II)	2503	2535	2410	2440	1515	1530	1351	1364
	Global	7882	8169	7572	7849	4821	4964	4359	4477
2100	Non-A5 (Group-I)	1772	1772	1683	1683	1109	1109	1032	1032
	Non-A5 (Group-II)	109	117	106	113	70	73	65	68
	A5 (Group-I)	7341	9947	7064	9572	4345	5647	3867	4942
	A5 (Group-II)	3581	3760	3447	3619	2100	2189	1853	1927
	Global	12803	15595	12299	14987	7624	9019	6817	7969

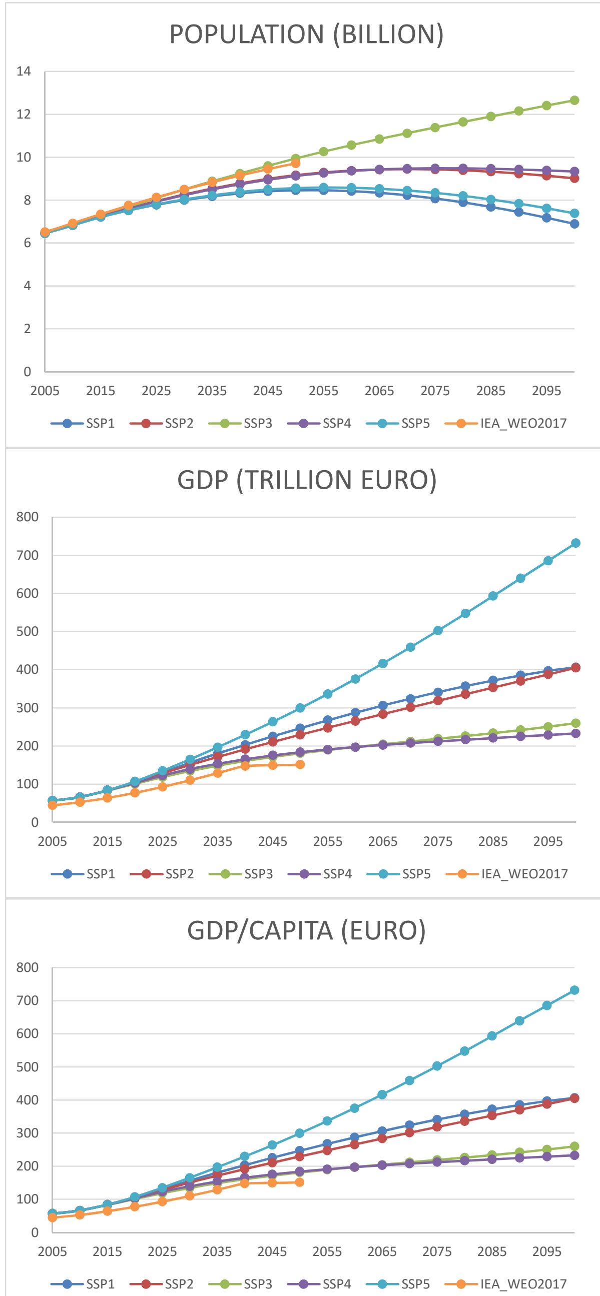
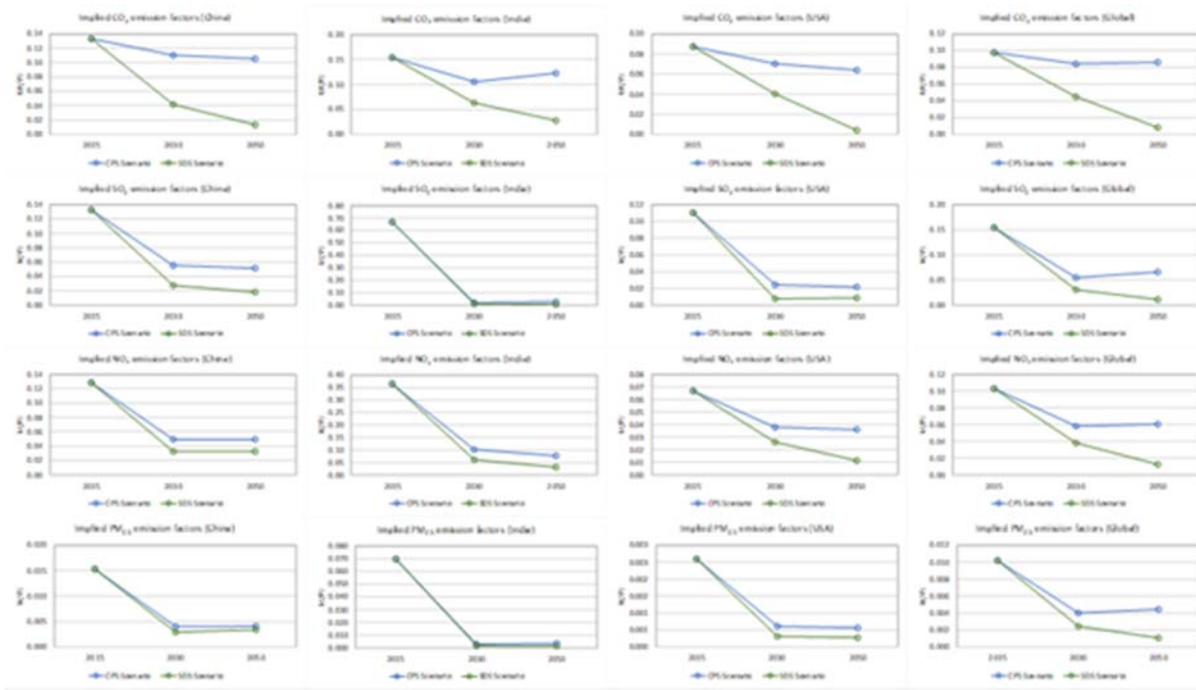


Figure S1: Comparison of future developments in global population and GDP between the IEA-WEO 2017 and the five Shared Socioeconomic Pathways (SSPs) scenarios.

Source: IIASA (2017)



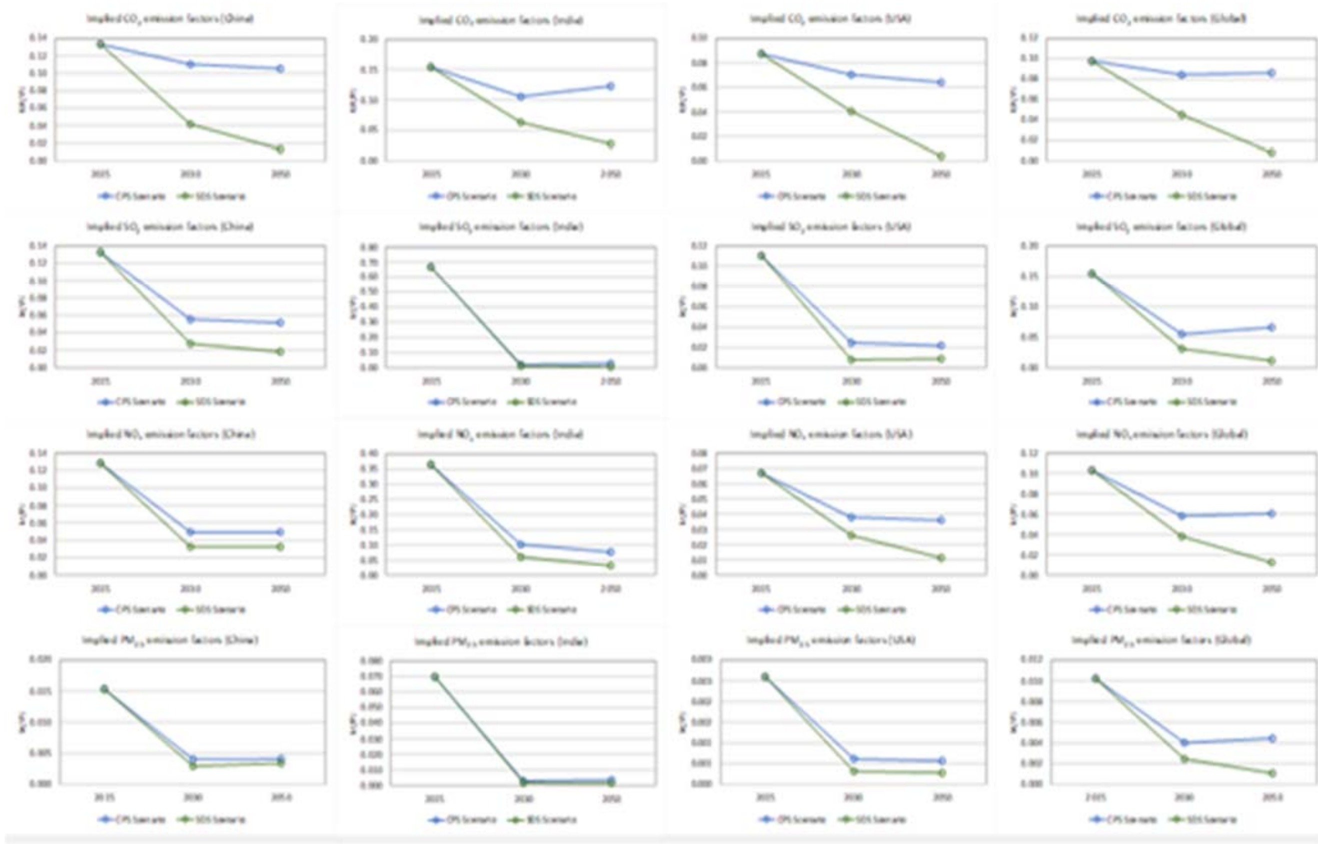
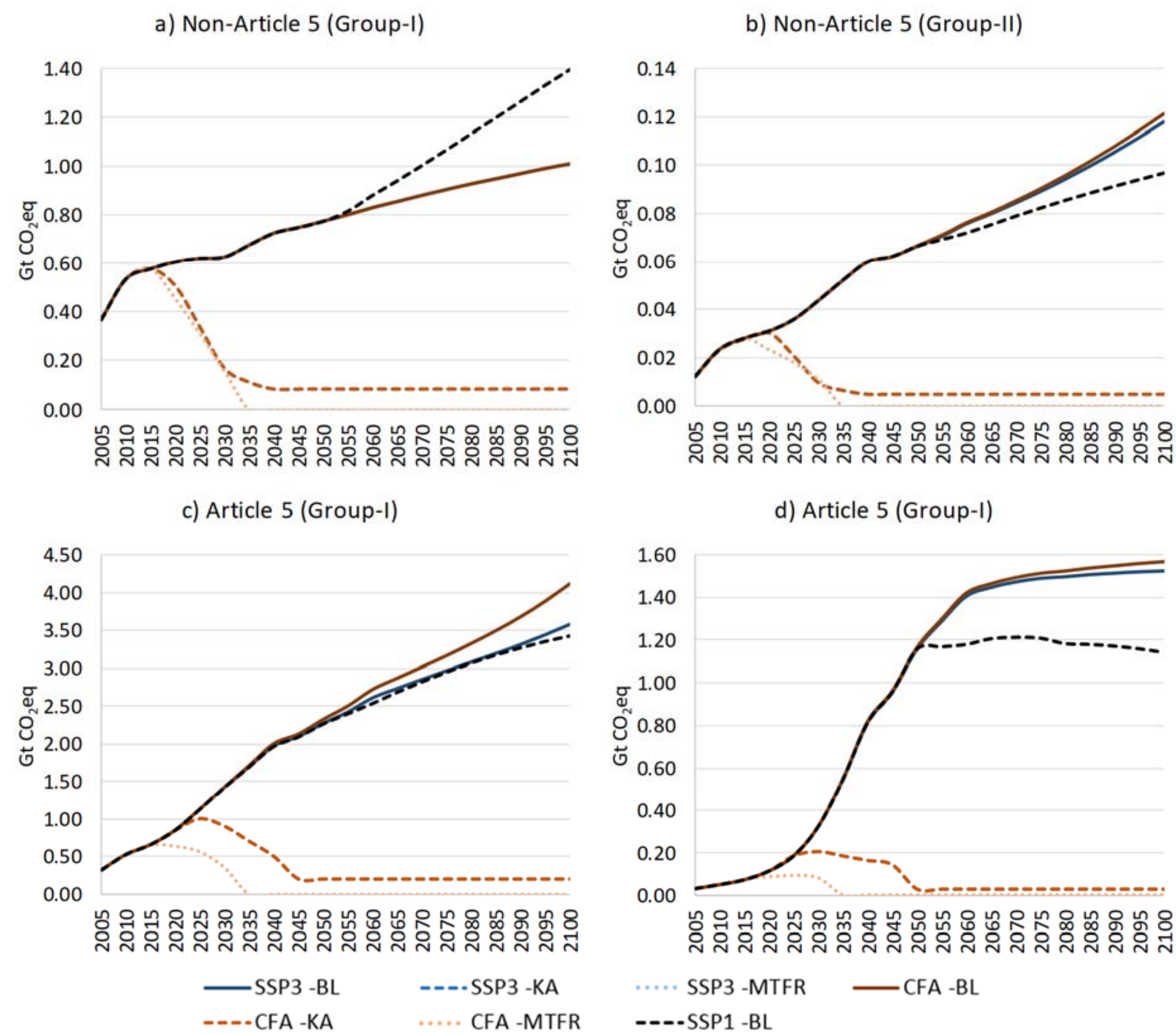


Figure S2: Implied emission factors for electricity production in the power plant sector for CO_2 and the air pollutants (SO_2, NO_x and $PM_{2.5}$) at global and select country level

Source: IIASA/GAINS Model available at: gains.iiasa.ac.at


a) Non-Article 5 (Group-I)
b) Non-Article 5 (Group-II)
c) Article 5 (Group-I)
d) Article 5 (Group-I)
Gt CO2eq
SSP3 -BL
SSP3 -KA
SSP3 -MTFR
CFA -BL
CFA -KA
CFA -MTFR
SSP1 -BL

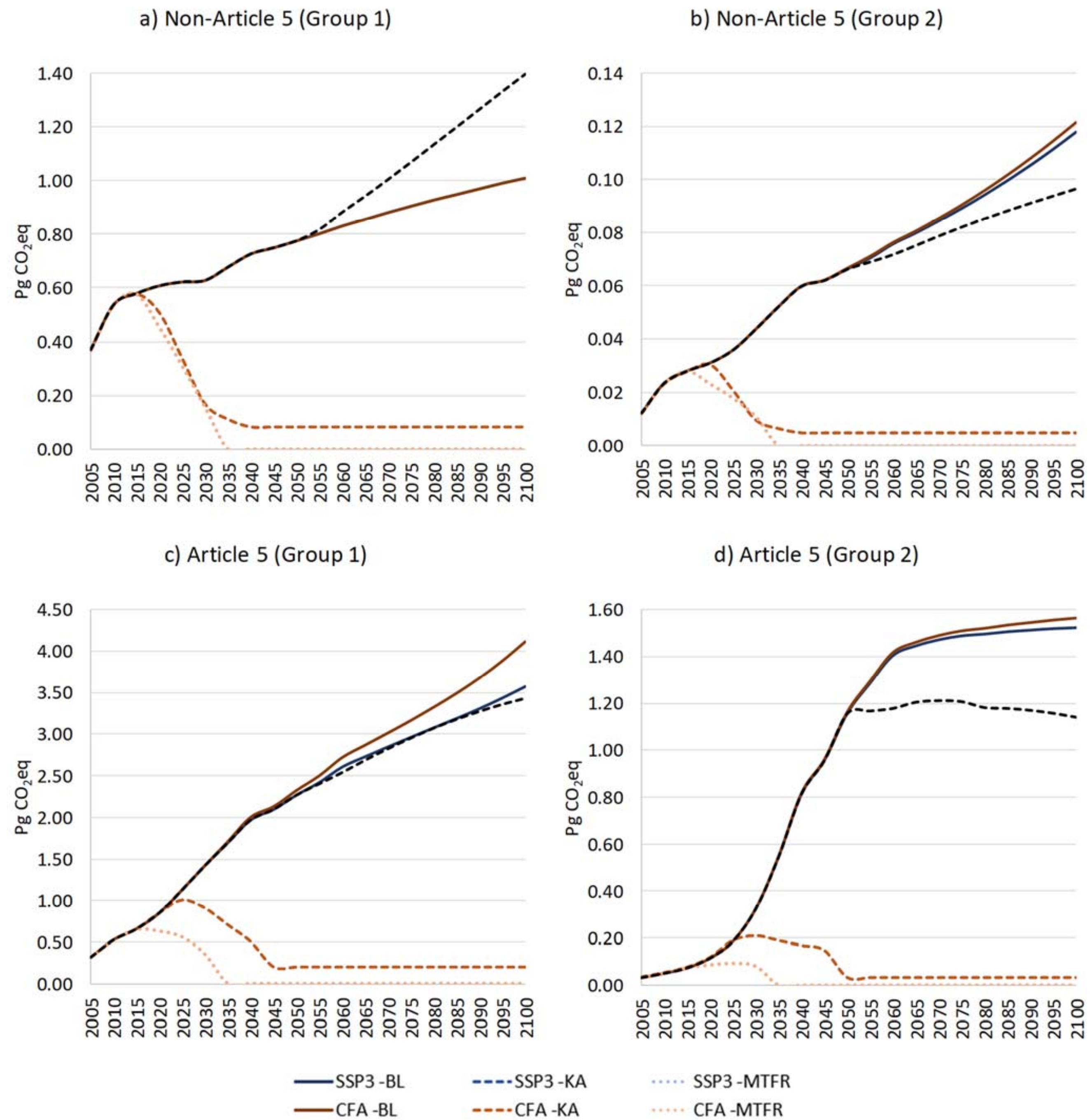


Figure S3: Baseline HFC/HCFC (~~Gt~~Pg CO_2eq) by different party groups (SSP3-BL and CFA-BL refer to SSP 3 and *Cooling for All* baselines, respectively)

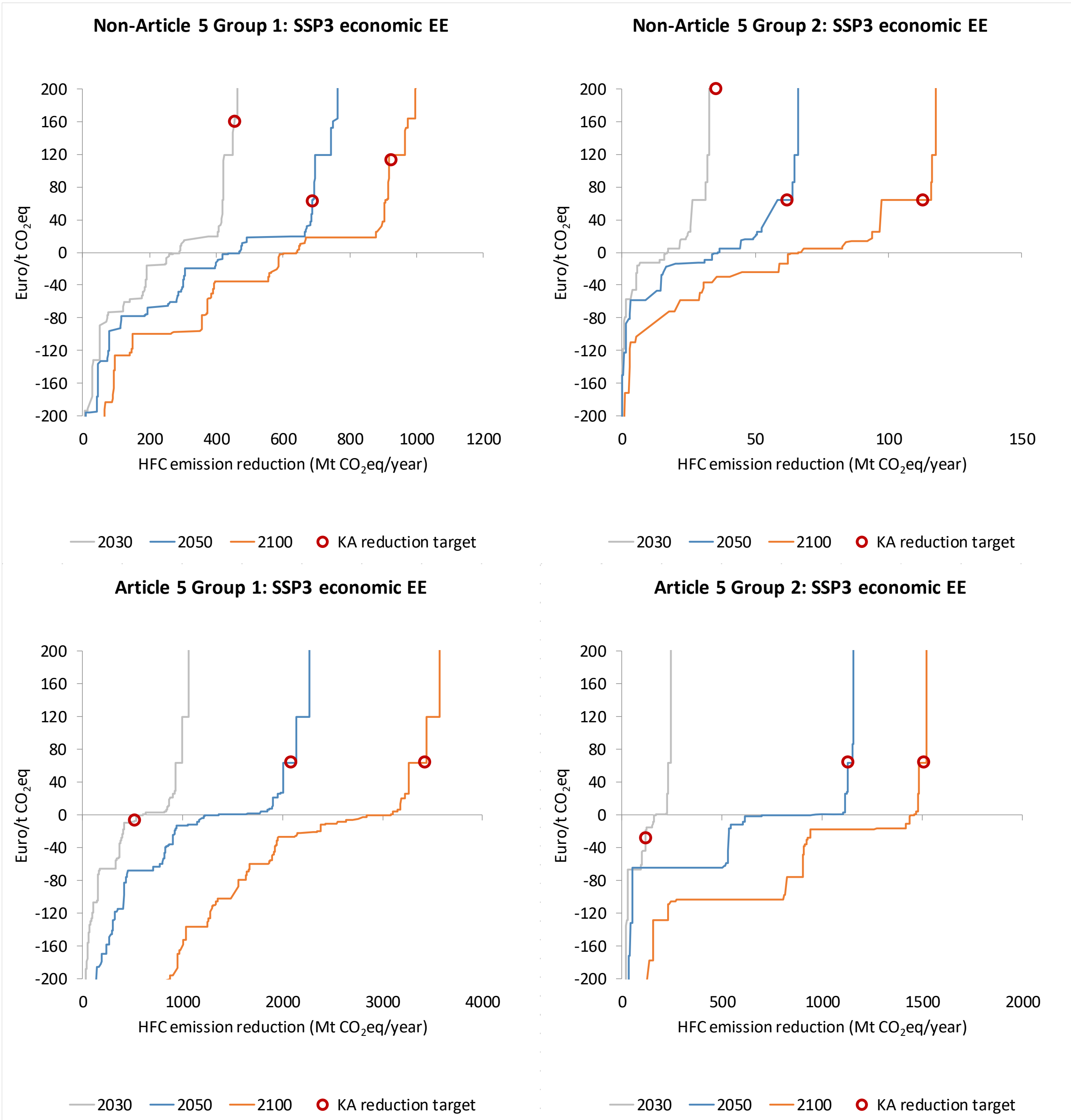
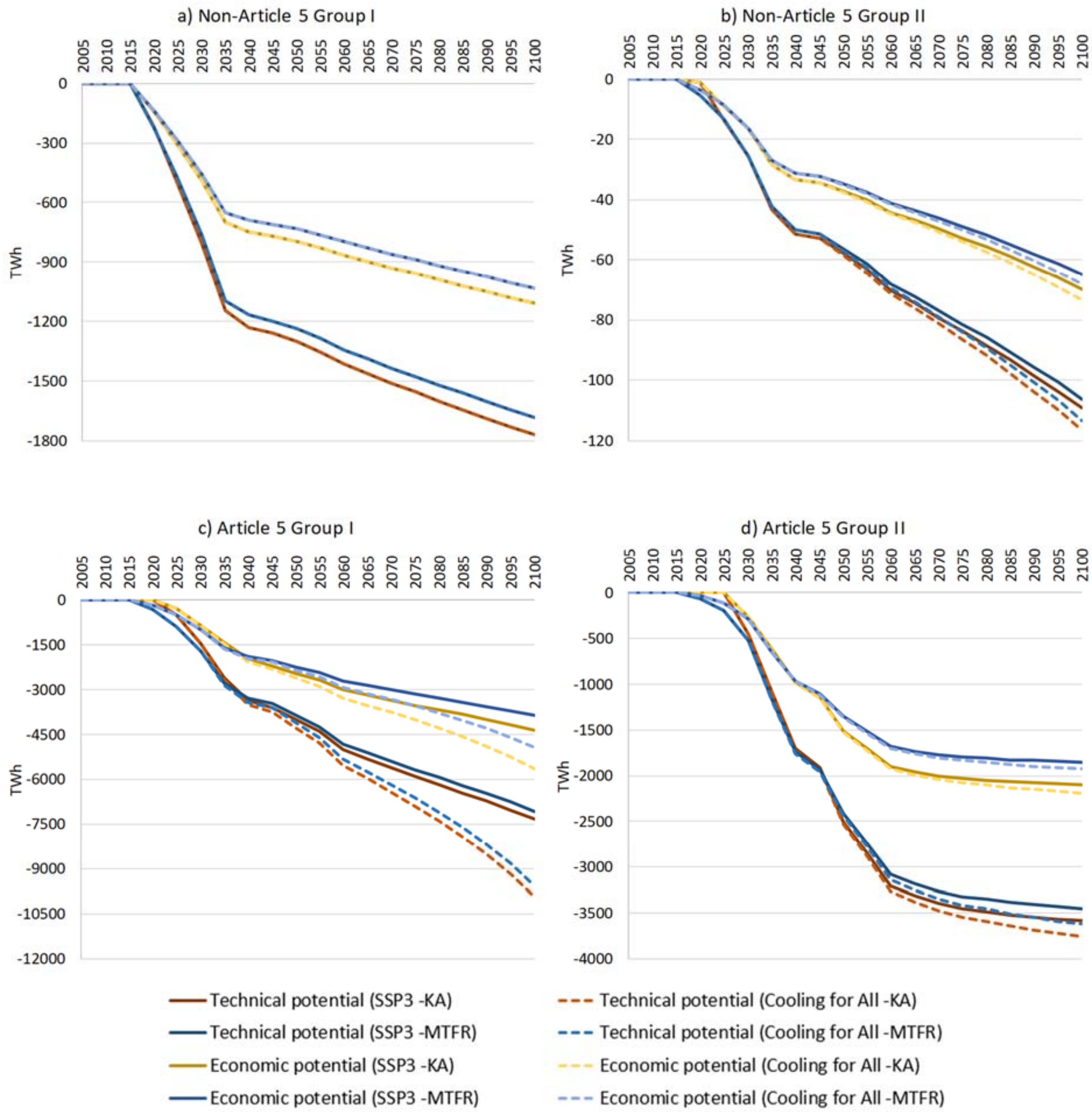


Figure S4: Marginal abatement cost curves (MACCs) starting from a pre-Kigali SSP3 baseline consistent with the IEA-WEO17 New Policies scenario and reducing HFC emissions by Kigali Amendment (KA) party groups under economic energy efficiency improvements and indicating the KA HFC reduction targets in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


a) Non-Article 5 Group I
b) Non-Article 5 Group II
c) Article 5 Group I
d) Article 5 Group II
TWh
Technical potential (SSP3 -KA)
Technical potential (SSP3 -MTFR)
Economic potential (SSP3 -KA)
Economic potential (SSP3 -MTFR)
Technical potential (Cooling for All -KA)
Technical potential (Cooling for All -MTFR)
Economic potential (Cooling for All -KA)
Economic potential (Cooling for All -MTFR)

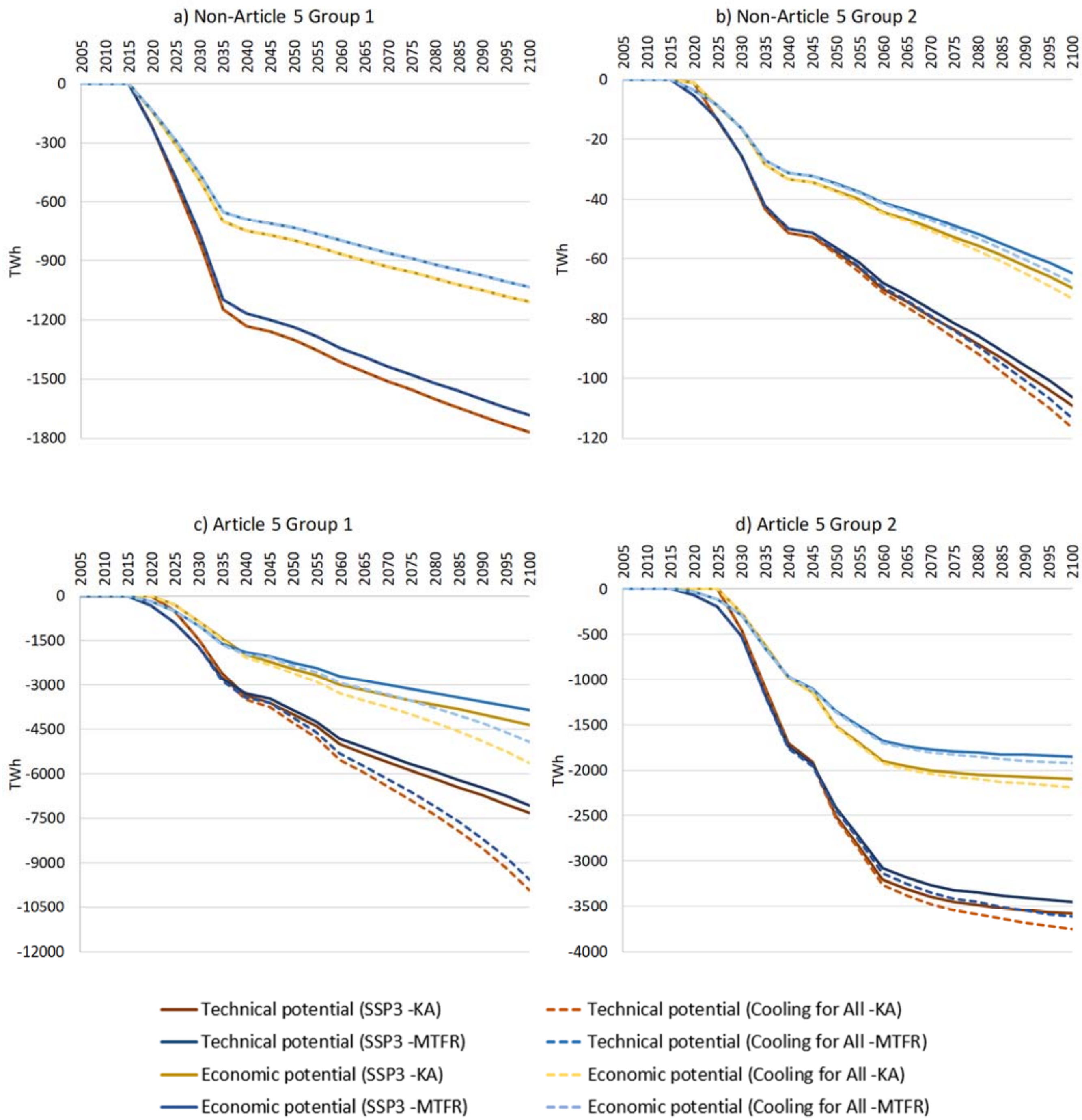
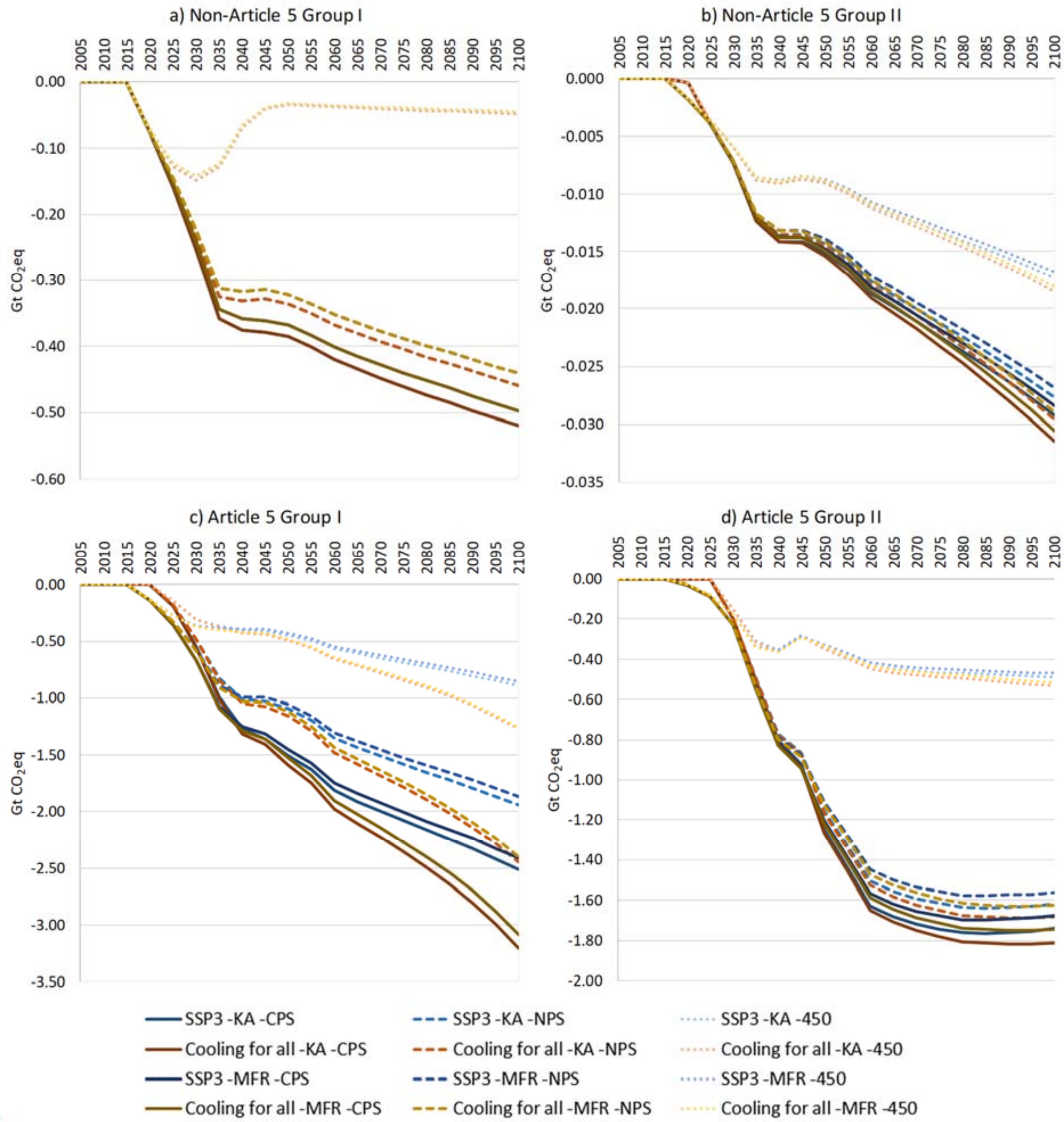


Figure S5: Technical and economic electricity saving (TWh) potential by different party groups



a) Non-Article 5 Group I
b) Non-Article 5 Group II
c) Article 5 Group I
d) Article 5 Group II
Gt CO_2eq
SSP3 -KA -CPS
Cooling for all -KA -CPS
SSP3 -MFR -CPS
Cooling for all -MFR -CPS
SSP3 -KA -NPS
Cooling for all -KA -NPS
SSP3 -MFR -NPS
Cooling for all -MFR -NPS
SSP3 -KA -450
Cooling for all -KA -450
SSP3 -MFR -450
Cooling for all -MFR -450

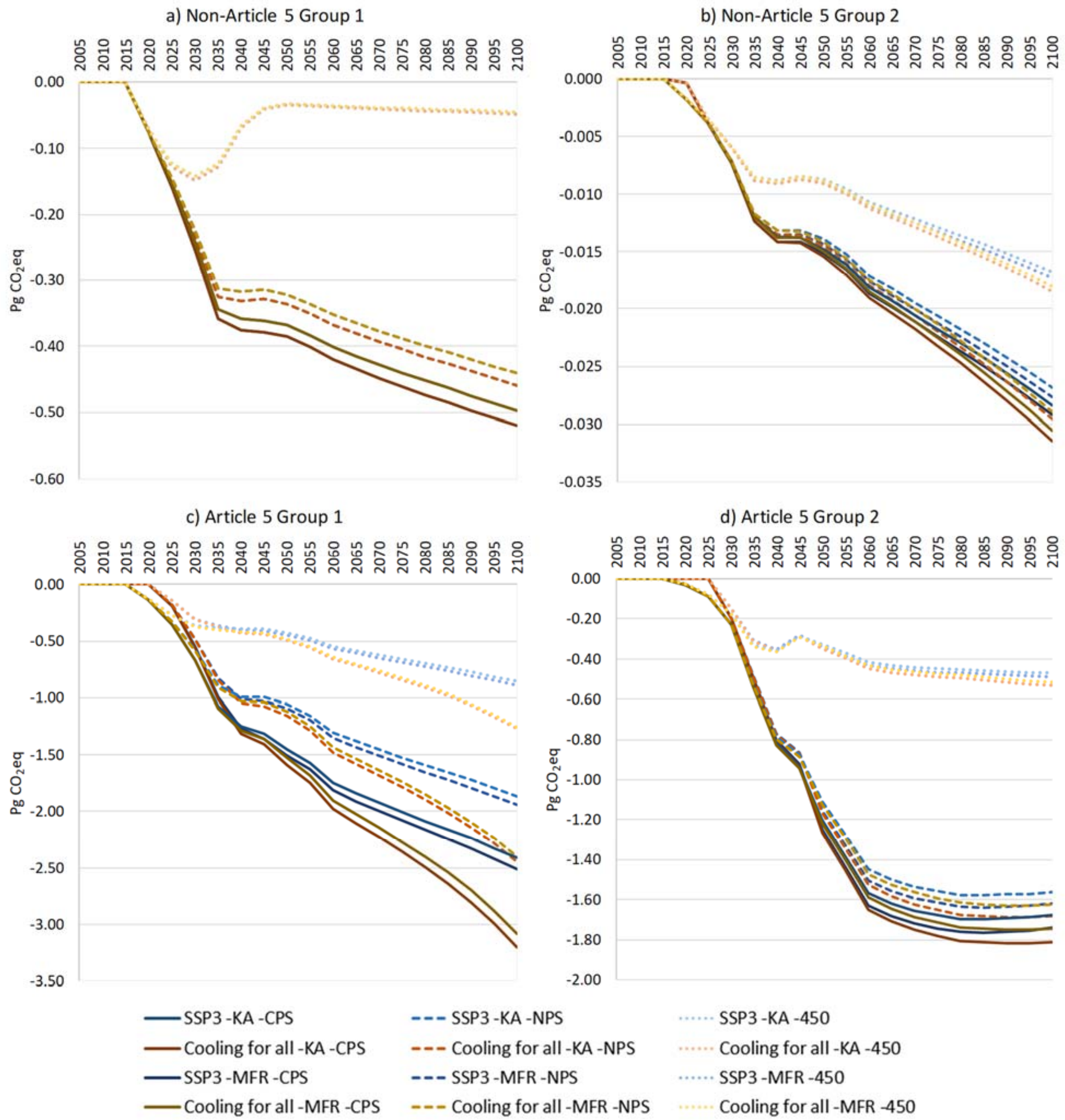
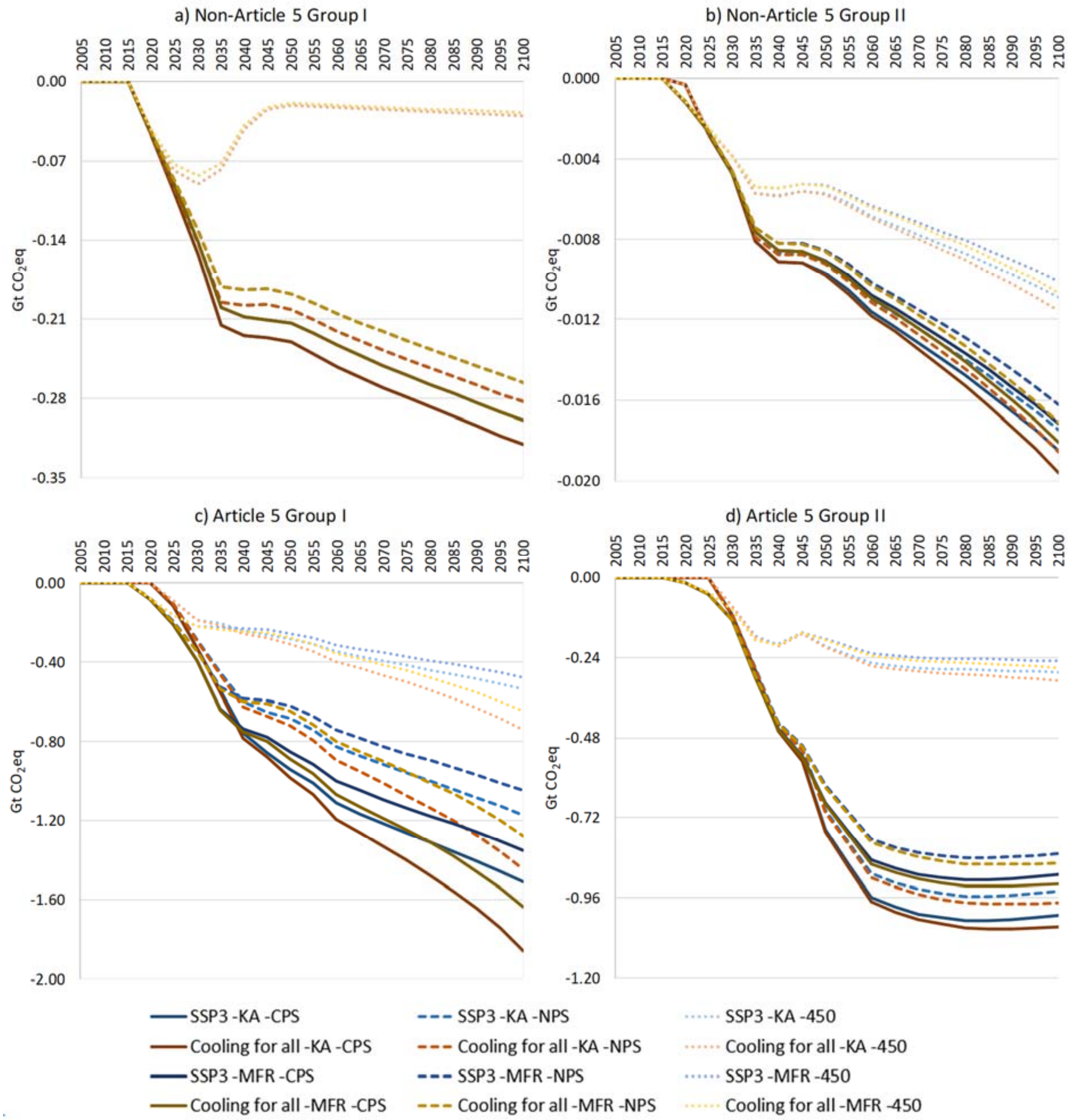


Figure ~~S5: GHG~~S6: Greenhouse gas emissions reductions in the baseline (SSP3 and *Cooling for All*) and alternative (~~KA and~~ Kigali Amendment -KA and Maximum Technically Feasible Reductions -MTFR) scenarios due to technical electricity savings potential by different party groups.



a) Non-Article 5 Group I
b) Non-Article 5 Group II
c) Article 5 Group I
d) Article 5 Group II
Gt CO2eq
SSP3 -KA -CPS
Cooling for all -KA -CPS
SSP3 -MFR -CPS
Cooling for all -MFR -CPS
SSP3 -KA -NPS
Cooling for all -KA -NPS
SSP3 -MFR -NPS
Cooling for all -MFR -NPS
SSP3 -KA -450
Cooling for all -KA -450
SSP3 -MFR -450
Cooling for all -MFR -450

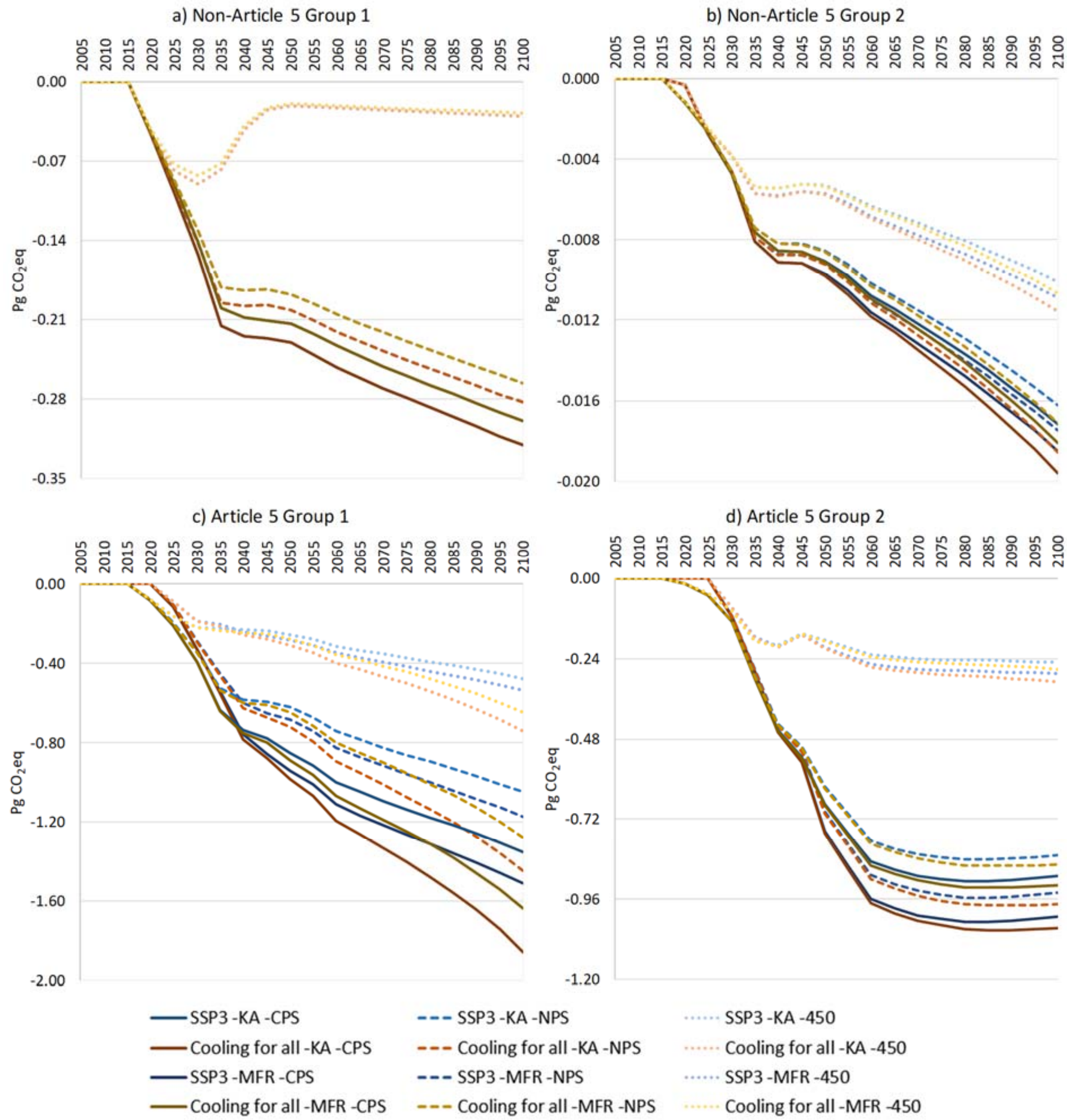


Figure ~~S6: GHG~~S7: Greenhouse gas emissions reductions in the baseline (SSP3 and *Cooling for All*) and alternative (~~KA and~~ Kigali Amendment -KA and Maximum Technically Feasible Reductions -MTFR) scenarios due to economic electricity savings potential by different party groups

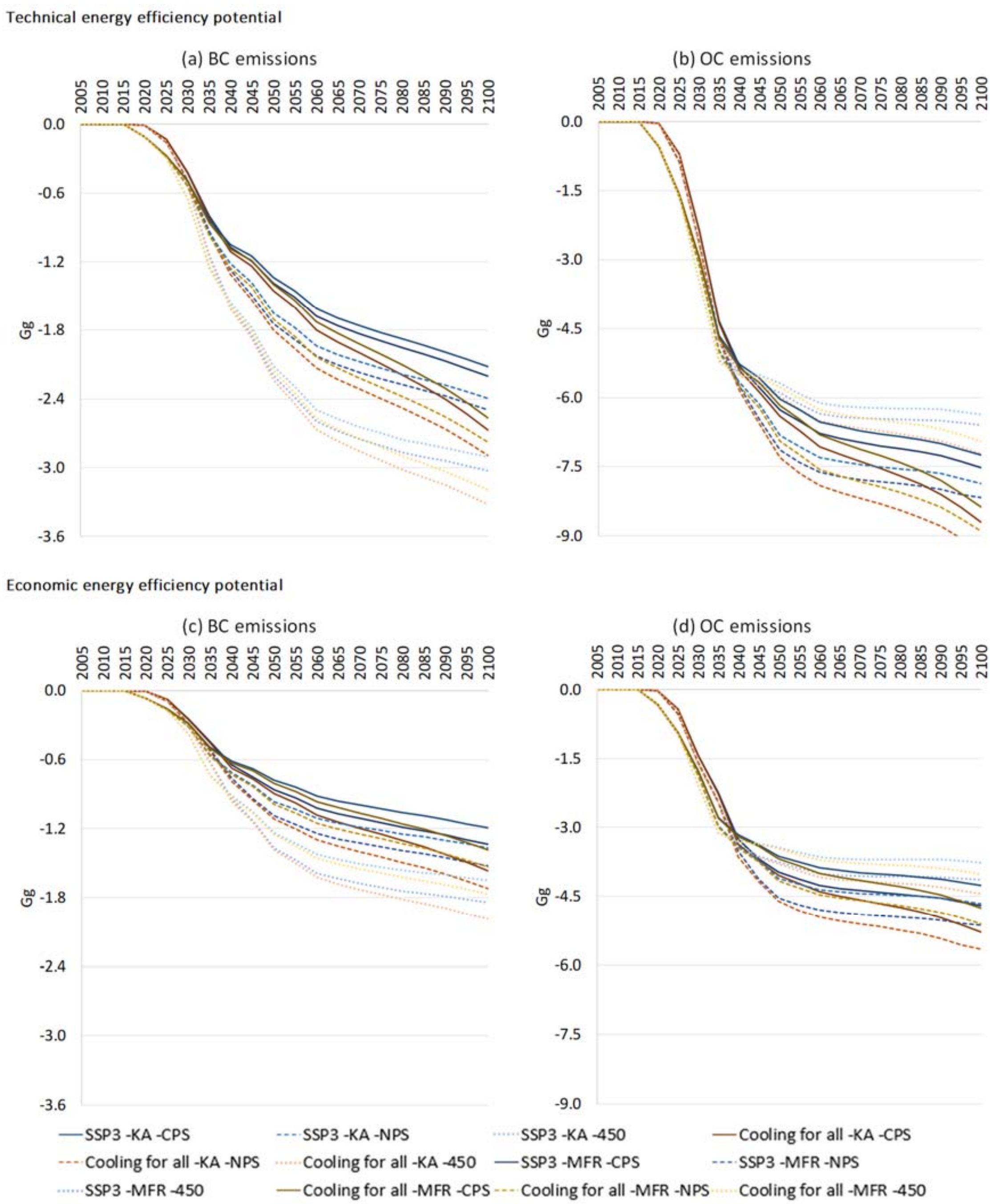


Figure S8: Impacts on BC/OC emissions due to electricity savings associated with alternative HFC phase-down pathways.

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