Achieving Paris climate goals calls for increasing ambition of the Kigali Amendment

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Hydrofluorocarbon emissions have increased rapidly and are managed by the Kigali Amendment to the Montreal Protocol. Yet the current ambition is not consistent with the 1.5 °C Paris Agreement goal. Here, we draw on the Montreal Protocol start-and-strengthen approach to show that accelerated phase-down under the Kigali Amendment could result in additional reductions of 72% in 2050, increasing chances of staying below 1.5 °C throughout this century.

Hydrofluorocarbon (HFC) refrigerants are factory-made chemicals produced for use in refrigeration, air-conditioning, insulating foams, fire extinguishers, solvents and aerosol propellants. Since their introduction, emissions of HFCs have grown rapidly as they are the primary replacement for ozone-depleting substances (ODSs) currently managed under the Montreal Protocol (MP)1–3. HFCs do not contain ozone-destroying chlorine or bromine atoms but are powerful GHGs and account for ~1.5% of global anthropogenic GHG emissions4. Without any controls, HFC emissions are expected to double by 2030 and nearly quadruple by 2050, compared to 2015 levels6–8.

In 2016, HFCs were included in the Kigali Amendment (KA) to the MP—a result of an international consensus that HFCs could be most effectively controlled through the phase-down of their production and consumption under the MP (ref. 9), complementary to mitigation under the UN Framework Convention on Climate Change (UNFCCC). The MP process accumulated experience and expertise to ensure a fast and efficient phase-down of HFCs, which are in the same family of gases, have similar chemical properties and are used in the same sectors as the ODSs that they are replacing. The MP also uses a ‘start and strengthen’ approach wherein controlled substances are phased out in an orderly and transparent schedule which is regularly evaluated and strengthened, through amendments, as markets innovate and adjust (Extended Data Fig. 1; ref. 9). Furthermore, unlike the Paris Agreement to the UNFCCC, the MP and its amendments are legally binding for countries that ratify them.

KA is a global agreement (in force since 1 January 2019) to phase-down consumption of HFCs of 80–85% by the late 2040s (Supplementary Table 1). Unlike previous MP amendments, which managed ODSs, the KA is primarily a climate treaty, therefore it is appropriate to evaluate the sufficiency of its ambition on the basis of its consistency with climate mitigation targets. The 2015 Paris Agreement established an ambitious target of limiting global mean temperature rise this century to well below 2 °C, preferably to 1.5 °C compared to pre-industrial levels, but did so in the context of broader international goals of sustainable development and poverty eradication. The 1.5 °C-consistent scenarios used in the IPCC Special Report on Global Warming of 1.5 °C (SR1.5) include a 75–80% reduction in HFC emissions by 2050, compared to 2010 levels2, along with deep and simultaneous reductions of CO2 and all non-CO2 climate-forcing emissions.

A recent IIASA study7 used the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model6 framework to develop a range of long-term scenarios for HFC emissions under varying degrees of stringency in climate policy and assessed co-benefits in the form of electricity savings and associated reductions in GHG and air pollutant emissions. Full compliance with the KA (Fig. 1a) is expected to achieve a 56% reduction in HFC emissions by 2050, compared to 2010 levels6. Hence, it will not achieve the 75–80% threshold set by 1.5 °C-consistent scenarios7. Full compliance with the KA phase-down schedule is estimated to avoid 0.2–0.4 °C additional warming by the end of this century10,11, which is significant but insufficient to achieve a 1.5 °C-consistent pathway. Despite the widely recognized success of the MP for phasing out ODSs faster7,12 and at a lower cost than originally assumed, some observers question whether the HFC-reduction process under KA is taking place quickly enough to adequately address the urgency of the climate crisis13. Considering the role HFC mitigation plays in 1.5 °C-consistent scenarios, enhancing the ambition of mitigation efforts by all parties to the MP is called for. In this study, we develop a series of alternative HFC phase-down scenarios (Fig. 1) consistent with the MP’s history and experience of a gradual increase in ambition.

KA defines HFC phase-down schedules for four different party groups. The first group (Article 5 Group 1) includes 136 primarily developing countries that make up all Article 5 countries with the exception of ten countries characterized by high ambient air temperatures forming a second group (Article 5 Group 2) and allowed less ambitious timing of targets. Non-Article 5 countries are primarily developed countries and under KA divided into two groups with 45 countries in a first group (non-Article 5, earlier start) and five in a second group allowed to start somewhat later (non-Article 5, later start).

We estimate HFC emissions (CO2eq using global warming potential GWP100 from IPCC/AR5 (ref. 13)) for all analysed scenarios (Fig. 2a). In a pre-KA baseline, HFC emissions increase to about 4.2 GtCO2eq by 2050, which is within the range of previous estimates (4.0–5.3 GtCO2eq) by Velders et al.14. With full KA compliance, global HFC emissions drop to 0.32 GtCO2eq by 2050, achieving 56% reduction compared to 2010 levels. Technology exists that, if deployed globally to a maximum extent, could achieve near-complete mitigation of HFC emissions one-decade sooner than the KA phase-down schedule, resulting in a cumulative reduction of ~77 GtCO2eq HFC emissions until 2050 (Supplementary Table 2). Such a rapid reduction is, however, infeasible on practical grounds and also inconsistent with the MP’s history of a phased step-wise approach to refrigerant management. Instead, we have analysed a set of more realistic reduction scenarios.
First, we analyse whether aligning Article 5 Group 2 countries with the higher ambition level of the Article 5 Group 1 (Article 5 Groups 1 and 2 alignment scenario) would result in achieving the Paris Agreement targets. The results show that this would not be the case (Fig. 2b, where the orange box indicates the 75–80% threshold set by 1.5°C-consistent scenarios). Next, we increase the ambitions of both Article 5 and non-Article 5 parties, resulting in achieving the Paris Agreement targets globally by 2050, however with different cumulative emissions until 2050 due to variations in the timing of adapted KA targets. If Article 5 and non-Article 5 party groups follow the KA phase-down schedules but step-up ambitions in their final phase-down step (starting in 2036 for non-Article 5 with Article 5 following only in year 2050) to 95% below baseline in the year 2050 (95% scenario), then the resulting cumulative reduction is 61 GtCO₂eq (Supplementary Table 2). If the Article 5 Groups 1 and 2 alignment scenario and the 95% scenario are combined (combined scenario), the resulting cumulative reduction is 63 GtCO₂eq. Finally, if the combined scenario is accelerated with a more ambitious target timeline (accelerated combined scenario), with non-Article 5 countries achieving 95% reduction already in 2036 and Article 5 countries starting earlier and achieving 95% in 2045, then a cumulative HFC-reduction potential of 69 GtCO₂eq can be achieved. The last scenario follows the example of the accelerated phase-out of HCFCs under the MP from 2007. In particular, for the period 2021–2030, the cumulative emissions are lower in the accelerated combined scenario compared to other scenarios.

The developing countries are less than 3 years away from the first HFC consumption compliance obligation of the KA applicable to Article 5 Group 1 countries. Much still needs to be done to ensure that all these countries are ready to comply with the 2024 cap on HFC consumption and production. In countries where HFC consumption is projected to exceed their baselines by 2024, there is an urgent need to implement actions towards a rapid transition to low-GWP refrigerants. In countries where HFC consumption is projected lower than their baselines by the agreed freeze year, there

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**Fig. 1 | HFC phase-down schedule of the Article 5 and non-Article 5 parties to the MP in KA and alternative scenarios.** Article 5 parties are divided into two groups: Group 1, most of the Article 5 parties; and Group 2, Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia and the United Arab Emirates. Group 2 (dashed black line) has a later freeze and phase-down steps compared with Group 1 (solid yellow line). Several non-Article 5 parties with dashed red line (Belarus, the Russian Federation, Kazakhstan, Tajikistan and Uzbekistan) have a different formulation for the calculation of baseline and have different initial phase-down steps (that is, the first two steps) from the other non-Article 5 parties with solid blue line. a, KA HFC phase-down schedules. b, Article 5 Groups 1 and 2 alignment scenario. c, 95% scenario. d, Combined scenario. e, Accelerated combined scenario.
are opportunities for faster implementation of the KA to achieve HFC emission reductions earlier than strictly required under KA.

KA provides an important opportunity and framework to control the production and consumption of HFCs resulting in reductions of both direct and indirect emissions from the cooling sector. Combining benefits from energy efficiency and climate-friendly cooling is vital to developing markets with rising cooling demand. Harnessing such opportunities by ensuring the transition to low-GWP refrigerants, combined with the adoption of energy-efficient cooling equipment, can potentially double the climate benefits of the HFC phase-down\(^3\) and save as much as 20% of the expected future global electricity consumption\(^4\). Lower electricity consumption also offsets the need to build new power plants and increases energy access across emerging economies. For example, transitioning to low-GWP refrigerants with enhanced energy efficiency in room air-conditioners in China could avoid the construction of ~300 coal-fired power plants (500 MW each) by 2050\(^5\). Therefore, an early HFC phase-down will foster sustainable growth with energy-efficient, innovative technologies that provide jobs, increase energy access and reduce air pollution while reducing consumer energy bills.

KA is a work in progress, but one that needs to be embraced and expanded upon in the global interests of mitigating climate change, just as the original MP has been instrumental in the recovery of the stratospheric ozone layer. An example of progressive legislation could be the HFC-reduction steps under the European Union F-gas regulation that is more ambitious than what is included in the KA\(^6\). Finally, if parties to the MP do not align early HFC phase-down policies with their economic transformation plans in the post-COVID era, they might not only become more vulnerable to climate shocks but also miss out on new technologies, investment and market access in a rapidly shifting global economy.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-022-01310-y.

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Methods

In developing the baseline HFC emissions under the IIASA study, the historical consumption of HFCs for major sources, that is, stationary and mobile air-conditioning and domestic refrigerators, have been derived in a consistent manner across countries, starting from a compilation of data on underlying drivers; for example, the number of vehicles by type, commercial floor space area, cooling degree days, per capita income, average household sizes, current equipment penetration rates and so on. Estimating HFC consumption in commercial, industrial and transport refrigeration, foams and other smaller HFC sources (for example, aerosols, fire extinguishers and solvents) is more challenging since it varies greatly between countries due to differences in industrial structures and consumption patterns. For these sectors, historical HFC consumption, as reported by industrialized countries to the UNFCCC, has been adopted when available.

For developing countries, information on HFC consumption in these sectors has been compiled from various published sources, alternatively, derived consistently from underlying activity data using default factors from literature. For the development of the baseline scenarios until 2040 we use the existing model setup in GAINS, which for global scenarios uses drivers consistent with macroeconomic and energy sector projections from the International Energy Agency. The extension in demand for cooling services between 2040 and 2100, expressed in tonnes of HFC consumed, is consistent with the growth in population and energy sector projections from the International Energy Agency. The extension in demand for cooling services between 2040 and 2100, expressed in tonnes of HFC consumed, is consistent with the growth in population and energy sector projections from the International Energy Agency. The extension in demand for cooling services between 2040 and 2100, expressed in tonnes of HFC consumed, is consistent with the growth in population and energy sector projections from the International Energy Agency.

In addition to the KA and Maximum Technically Feasible Reduction (MTFR) scenarios as explained in the IIASA study, we analyse four scenarios for HFC phase-down to achieve the Paris Agreement targets by 2050. In the Article 5 Groups 1 and 2 alignment scenario, we assume that Article 5 Group 2 countries join the Article 5 Group 1 phase-down schedule immediately as shown in Fig. 1b. Note that Article 5 Group 2 countries have a later freeze date (Supplementary Table 1) and delayed phase-down steps compared with Article 5 Group 1 under the KA. In the 95% scenario, we assume that all party groups will follow the KA phase-down schedules but, in addition, the final phase-down step by 2050 will be 95% of baseline, valid for all party groups, as shown in Fig. 1c. In the combined scenario, we assume that Article 5 Group 2 countries join the Article 5 Group 1 phase-down schedule immediately as in the case of the Article 5 Groups 1 and 2 alignment scenario; in addition, the final phase-down step by 2050 will be 95% of baseline and, just like in the case of the 95% scenario, be valid for all party groups, as shown in Fig. 1d. Finally, the accelerated combined scenario is designed following the example of the accelerated phase-out of HCFC in 2007 (Extended Data Fig. 1) as shown in Fig. 1e. In the case of the HCFC example, the accelerated phase-out was agreed upon 11 years after the freeze date set for non-Article 5 countries and 3 years after the first phase-out step but before the freeze date set for Article 5 countries.

Data availability

Global HFC emissions data used in the baseline and alternative scenarios are available at: https://github.com/ppurohit76/Accelerating-HFC-phase-down-under-the-Kigali-Amendment. Source data are provided with this paper.

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Author contributions

All authors contributed to parts of the research and analysis. P.P., N.B.-P. and Z.K. conceived of and coordinated the writing of the paper. P.P. and L.H.-I. performed the analysis and P.P. developed the initial draft of the paper. All authors contributed to the interpretation and analysis of the results as well as writing the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Fig. 1 | Major milestones in the history of stratospheric ozone depletion. This timeline highlights milestones related to the history of ozone depletion. Events represent the occurrence of important scientific findings, the completion of international scientific assessments, and milestones of the Montreal Protocol. Figure reproduced from ref. 6 [public domain].