Article

Rethinking time-lagged emissions and abatement potential of fluorocarbons in the post-Kigali Amendment era

Heping Liu[1], Huabo Duan [2] ✉, Ning Zhang [3], Yin Ma[1], Gang Liu[4,5], Travis Reed Miller [6], Ruichang Mao[7], Ming Xu[8], Jinhui Li [8] & Jiakuan Yang [2] ✉

The Montreal Protocol has been successful in safeguarding the ozone layer and curbing climate change. However, accurately estimating and reducing the time-lagged emissions of ozone-depleting substances or their substitutes, such as produced but not-yet-emitted fluorocarbon banks, remains a significant challenge. Here, we use a dynamic material flow analysis model to characterize the global stocks and flows of two fluorocarbon categories, hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), from 1986 to 2060. We assess emission pathways, time-lagged emission sizes, and potential abatement measures throughout different life cycle stages while focusing on the role of banked fluorocarbons in global and regional decarbonization efforts in the post-Kigali Amendment era. Although fluorocarbon releases are expected to decline, the cumulative global warming potential (GWP)-weighted emissions of HCFCs and HFCs are significant; these will be 6.4 (±1.2) and 14.8 (±2.5) gigatons CO_2-equivalent, respectively, in 2022–2060 in our business-as-usual (BAU) scenario. Scenario analysis demonstrates that implementing currently available best environmental practices in developed economies can reduce cumulative GWP-weighted emissions by up to 45% compared with the BAU scenario.

The Montreal Protocol on Substances that Deplete the Ozone Layer of 1987 sets controls on the production and consumption of ozone-depleting substances (ODSs). It is one of the most successful environmental treaties, and the speed and universality of its implementation have been extensively applauded for protecting the ozone layer[1–3]. By limiting ODSs, the Montreal Protocol and its amendments are predicted to inhibit global temperature increase by as much as 2–3 °C[4,5].

According to the Montreal Protocol, the phase-out of chlorofluorocarbon (CFC) production and consumption in all nations was accomplished globally around 2010[6]. The major substitutes for CFCs, hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), are powerful greenhouse gases (GHGs) and have not yet been completely phased out[7,8]. Both HCFCs and HFCs have been used in various applications, including refrigeration, air conditioning, and as foaming agents for insulation[9–11] (Supplementary Figs. 1–4). There is still sub-

[1]Guangdong Provincial Key Laboratory of Petrochemical Pollution Process and Control, School of Environmental Science and Engineering, Guangdong University of Petrochemical Technology, Maoming, Guangdong, China. [2]School of Environmental Science and Engineering, Hubei Key Laboratory of Multimedia Pollution Cooperative Control in Yangtze Basin, Huazhong University of Science and Technology, Wuhan, China. [3]Leibniz Institute of Ecological Urban and Regional Development (IOER), Dresden, Germany. [4]College of Urban and Environmental Sciences, Peking University, Beijing, China. [5]Institute of Carbon Neutrality, Peking University, Beijing, China. [6]Department of Civil and Environmental Engineering, University of Maine, Orono, ME, USA. [7]DTU Sustain, Department of Environmental & Resource Engineering, Technical University of Denmark, Lyngby, Denmark. [8]School of Environment, Tsinghua University, Beijing, China. ✉e-mail: huabo@hust.edu.cn; jkyang@hust.edu.cn

stantial production and consumption of HCFCs and HFCs at approximately 1.5–2.0 million metric tons (Mt) annually, with more than half of these events occurring in China[10] (Supplementary Fig. 5). The Article 5 (A5) parties of the Montreal Protocol, mostly developing economies, including China and India, have been phasing down their production and consumption of HCFCs since 2013 but will only completely phase them out by 2040[12]. In the 2016 Kigali Amendment to the Montreal Protocol, parties agreed to include some HFCs as controlled substances. The Kigali Amendment outlines a target reduction of 80%–85% in global HFC production and consumption by 2047[7], with respect to baseline levels, as defined in the caption of Supplementary Fig. 6.

Although the routes for phase-down or phase-out production and consumption of HCFCs and HFCs are well defined, special attention and further investigation are required to address the potential release of banked fluorocarbons that were previously consumed and remain in products. Emissions from banks are time-lagged due to the long lifespans of host products, such as fluorocarbon refrigerants in refrigerators and air conditioners or fluorocarbon blowing agents used in building insulation foams (Supplementary Fig. 7). Currently, the regulatory obligations to restrict the emissions of banked fluorocarbons mainly depend on national or regional regulations, such as those in Japan, the United States, and European Union members[13–15]. Therefore, these "delayed emissions" can be significant in the coming decades, especially when considering the typically unregulated or mismanaged scrap fluorocarbons in A5 parties[16,17].

Many studies have examined fluorocarbon banks and their associated emissions[11,16–29]. These studies were typically conducted using a "bottom-up" approach[11,16,17,20–24], a "top-down" approach[25–28], or a Bayesian probabilistic model[18,19]. The top-down approach is particularly effective in the assessment of temporal trends in historical emissions derived from atmospheric measurements[25–28]. For instance, atmospheric measurements have recently indicated declining trends in global emissions of HCFC-22 and HCFC-142b[29]. In contrast, it is concerning that global emissions of HCFC-141b have continually increased since 2017 despite reported reductions in production and consumption for dispersive uses[27–29]. Previous "bottom-up" or "Bayesian probabilistic model" studies mainly focused on the evaluation of bank sizes and emissions associated with these banks[18–22], thereby limiting their capability to assess the reduction potential of emissions from fluorocarbon banks. For example, using the Bayesian probabilistic model, Lickley et al.[18,19] estimated and projected the banked volumes of CFCs and selected HCFCs (HCFC-22, HCFC-141b, and HCFC-142b) in various equipment and products. Their studies successfully reconciled the discrepancies between top-down and bottom-up emission estimates but did not disaggregate the estimates by region. Velders et al.[20,21] simulated the banks and emissions of 10 categories of HFCs from 12 use sectors by 11 global regions from 1990 to 2050, enabling an estimate of the efficacy of the Kigali Amendment in curbing the climate impact of HFC emissions. However, these studies[18–21,25] could barely provide targeted or tailored abatement measures for delayed emissions resulting from banked fluorocarbons. Through integrated and comprehensive analysis, Bai et al.[24] examined a pathway toward China's near-zero HFC territorial and exported emissions by 2060. Although their study covered the mitigation of emissions from banked HFCs, further investigation is required to explore significant HCFC and HFC banks and associated emission mitigation strategies on global or regional scales.

To address this, we develop a dynamic material flow analysis (MFA) model that characterizes the stocks and flows of HCFCs and HFCs at the equipment and product level and across diverse regions, sectors, and life cycle stages (Methods and Supplementary Methods). We first model historical patterns during 1986–2021 and then project emission pathways and the corresponding ozone depletion potential (ODP) and global warming potential (GWP) through 2060 in various scenarios (see Methods). We assess emission pathways and hotspots

and highlight the role of banked fluorocarbons in decarbonization efforts in the post-Kigali era. Furthermore, we evaluate the implementation of the Best Environmental Practices (BEPs) as potential abatement measures, along with the Kigali Amendment, for future endeavors. BEPs encompass various commercially proven technologies and methods for reducing emissions (Supplementary Methods). The findings can probably help formulate targeted mitigation policies, considering fluorocarbon categories and regional, sectoral, and life cycle stage differences.

Results and discussion
Global warming potential-weighted emission by life cycle
In Fig. 1a, the curve graph shows the annual and cumulative mass emissions of the two fluorocarbon categories, classified by life cycle stage. The corresponding annual and cumulative GWP-weighed emissions in terms of a 100-year time horizon are shown in Fig. 1b. In this study, the production and consumption of fluorocarbons by parties are expected to be subject to the Montreal Protocol, its amendments, and national and regional regulations. In our business-as-usual (BAU) scenario, the peak of the total annual GWP-weighted emissions occurs around 2023, with 1050 (±190) megatons (Mt) CO_2-equivalent (CO_2e), which will drop by several orders of magnitude to 70 (±10) Mt CO_2e in 2060. Because the total GHG emissions globally in 2022 were 40.5 gigatons (Gt) CO_2e[30], we estimated that the two fluorocarbon categories contributed approximately 2%–3%.

The annual GWP-weighed emissions of the use stage are 2–3 times larger than those of the end-of-life (EoL) stage prior to 2030. We project that the emissions from the EoL stage will surpass those from the use stage by the late 2030 s because of the further phase-down of HCFC and HFC production and consumption. The GWP-weighted emissions from the use stage peaked around 2021 at 760 (±140) Mt CO_2e, whereas the EoL stage is expected to peak around 2030 at 340 (±50) Mt CO_2e. This significant difference is mainly attributed to the high release rates of fluorocarbons during the use phase, especially from the industrial and commercial refrigeration (ICR) sector and the mobile air conditioner (MAC) sector. Leakages, servicing, relocation, accidents, and repairs may result in refrigerant release. The annual emission rates of refrigerants from ICR and MAC equipment in use can be as high as 10–35% of the initial charges[31,32] (Supplementary Tables 6–11). We assume that a considerable portion of the released fluorocarbons is refilled[33]. For example, in the MAC sector, refrigerant refilling occurs when the residual rate of the initial charge is below 50%[33]. In some ICR equipment, when the mass of fluorocarbon refrigerants falls below 70% of the initial charge, operational capacity and cooling performance may be significantly reduced, and refilling is required[33,34]. On another note, the recovery and destruction of scrap fluorocarbons during the EoL stage have been well implemented in a few non-A5 parties. For example, over 90% of the refrigerant in EoL room air conditioner (RAC) equipment is being recovered in Japan[35].

Global warming potential-weighted emission per fluorocarbon
The intentional substitution of the production and consumption of HCFCs with HFCs over time caused a lagged shift in the share of emissions. In the BAU scenario, the annual GWP of HCFC emissions peaked at 490 (±100) Mt CO_2e around 2018 and decreased slightly to 470 (±100) Mt CO_2e in 2021. The annual GWP of HFC emissions is expected to peak at 660 (±100) Mt CO_2e around 2029. These trends align broadly with the phase-down plan for the production and consumption of HCFCs and HFCs from the A5 parties (Supplementary Fig. 6).

Although the phase-down schedule under the Montreal Protocol and its amendments significantly reduces GWP-weighted emissions from the two fluorocarbon categories, there will still be large time-lagged emissions in the coming four decades in the BAU scenario. The cumulative GWP-weighted emissions during 2022–2060 caused by the release of HCFCs and HFCs will be 6.4 (±1.2) and 14.8 (±2.5) Gt
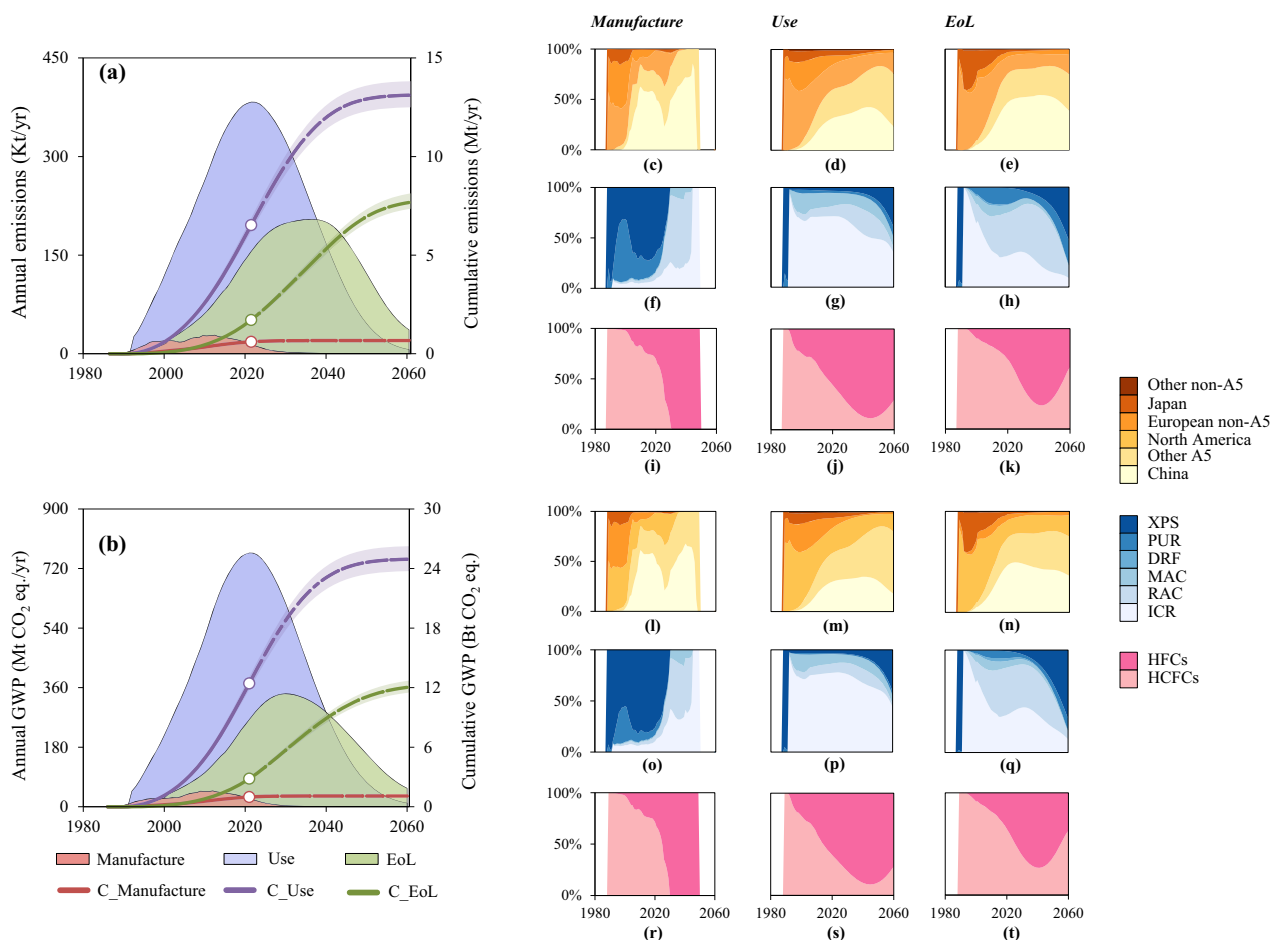
Fig. 1 | Estimates and projections of mass emissions and global warming potential (GWP)-weighted emissions of hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) in business-as-usual (BAU) scenario, 1986–2060. a Annual mass emissions from various life cycle stages; **b** corresponding annual GWP-weighted emissions. Contributions (%) by mas (**c**–**k**) and GWP-weighted emissions (**l**–**t**) of each region, end-use sector, and fluorocarbon categories across life cycle stages. A5 parties include China and other A5 parties, while non-A5 parties include Japan, North America (Canada and the USA only), European non-A5 and other non-A5 parties. End-use sectors include domestic refrigerator and freezer (DRF), room air conditioner (RAC), mobile air conditioner (MAC), industrial and commercial refrigeration (ICR), polyurethane rigid (PUR) foam, and extruded polystyrene (XPS) foam. The life cycle stages include manufacture, use and end-of-life (EoL).

CO$_2$e, respectively. Approximately 70% and 35% (by mass of CO$_2$e) of the cumulative HCFC and HFC emissions, respectively, are projected to be derived from existing banks (Supplementary Fig. 8). Thus, the decarbonization of HCFC and HFC emissions will rely not only on effective phase-out plans under the Montreal Protocol and its Kigali Amendment but also on the resolution of lag emissions from banks.

Global warming potential-weighted emission per region

Non-A5 parties have partially implemented BEPs to a certain extent for equipment or products containing fluorocarbons, which involve regular checks and repairs to prevent leakage and malfunction in in-use products or equipment, as well as rigid management of obsolete products or equipment[8,13–15] (Supplementary Methods). For example, Japan enacted its Fluorocarbon Recovery and Destruction Law (now Act on Rational Use and Proper Management of Fluorocarbons) in 2001 to limit fluorocarbon emissions during recovery and destruction activities in the domestic refrigerator and freezer (DRF), RAC, MAC, and ICR sectors[13]. In 2015, the European Commission issued its Current F-gas Regulation with rigid measures such as the control of leaks, proper servicing of equipment, and recovery of chemicals in obsolete equipment[14]. In 2021, the combined GWP of fluorocarbon banks in this study was 12.9 (±2.0) Gt CO$_2$e globally. China ranked first with banks of 4.2 (±0.4) Gt CO$_2$e, followed by North America with 3.5 (±0.5) Gt CO$_2$e,

the other A5 nations with 3.3 (±1.0) Gt CO$_2$e, European non-A5 nations with 1.2 (±0.1) Gt CO$_2$e, and finally, the rest of the world contributed approximately 0.7 (±0.04) Gt CO$_2$e (Supplementary Fig. 9). These fluorocarbon banks resulted in a total global emission of 1.0 (±0.2) Gt CO$_2$e in 2021 (Supplementary Fig. 10), of which China accounted for 35%, followed by the other A5 nations with 30%, North America with 22%, and the rest of the world with 14%, due to BEPs implemented in some non-A5 parties.

The cumulative GWP of the two fluorocarbons emitted from non-A5 parties between 1986 and 2021 was 9.2 (±1.2) Gt CO$_2$e. Furthermore, approximately 3.8 (±0.5) Gt CO$_2$e of emissions were avoided because of the application of BEPs in those countries. In contrast, A5 parties accounted for a cumulative GWP of 7.0 Gt (±1.4) CO$_2$e from 1986 to 2021, with less than 1% mitigated by applying BEPs. Unlike in non-A5 parties, BEPs in A5 parties are extremely insufficient. There are obstacles to applying BEPs in A5 parties, such as a lack of holistic and sound management systems and insufficient financial and supervisory support. Differing time frames exist for the phase-down or phase-out schedule of HCFC and HFC production and consumption in non-A5 and A5 parties[12,29]. If such BEPs persist, it is expected that China will account for 38% of the cumulative GWP-weighted emissions from HCFC and HFC during 2022–2060, followed by other A5 nations with 35%, North America with 19%, and the rest of the world with 8%.

When examining the per capita GWP from cumulative fluorocarbon emissions between 1986 and 2060, North America ranks first with an accumulative release of 23,700 (±3700) kg CO_2e per capita in the BAU scenario, followed by Japan with 13,200 (±600) kg CO_2e, other non-A5 parties with 8700 (±400) kg CO_2e, China with 8600 (±700) kg CO_2e, and European non-A5 parties with 4700 (±700) kg CO_2e. The other A5 parties have the lowest intensity, with 2200 (±700) kg CO_2e per capita (Supplementary Fig. 11).

Global warming potential-weighted emission per sector

In past decades (1986–2021), the ICR sector has been the highest contributor to the GWP-weighted emissions of fluorocarbon (66%), followed by the RAC (13%), MAC (10%), polyurethane rigid (PUR) and extruded polystyrene (XPS) foam (10%), and DRF (1%) sectors (Fig. 1o–q). In 2022–2060, the ICR sector will also rank first (57%), followed by the RAC (24%), PUR and XPS foam (12%), MAC (7%), and DRF (1%) sectors in the BAU scenario (Supplementary Fig. 12). Refrigerant-related applications (ICR, RAC, and MAC) will have a total impact of 88%, highlighting their significance in emission abatement. The projected increase in the contribution of the RAC sector can partly be attributed to the rapid growth of RAC equipment consumption in A5 parties and the adoption of low-GWP HFCs in non-A5 parties.

Scenarios analysis for emission mitigation potential

The abatement potential of mass emissions and the corresponding GWP and ODP of the two fluorocarbon categories subject to scenario-based analysis are shown in Fig. 2. In the BAU scenario, the cumulative ODP and GWP are projected to reach 260 (±50) kilotons (Kt) CFC-11-equivelant (CFC-11e) and 21.2 (±3.7) Gt CO_2e from 2022 to 2060,

respectively. These projections exclude a reduction of 39 (±4) Kt CFC-11e and 4.5 (±0.7) Gt CO_2e through the implementation of BEPs in non-A5 parties. In the optimal scenario (S4), there is a cumulative potential reduction of approximately 9.7 (±1.5) Gt CO_2e between 2022 and 2060, accounting for 45% of the total emissions in the BAU scenario. Globally, the ICR and RAC sectors will be the major contributors to the total emission abatement, accounting for 38% and 37%, respectively, followed by the MAC sector with 11% and the XPS and PUR foam sectors with 10% and 3%, respectively. Proper recovery and destruction of fluorocarbon refrigerants from EoL equipment can effectively reduce emissions from the RAC sector. However, compared with the significant contribution of the ICR sector to GWP-weighted emissions in the coming decades (57%), there is a noticeable disparity in its role toward emission mitigation (38%). This is due to the high release rate of fluorocarbons from ICR equipment during the use stage, particularly from large and medium-sized refrigeration equipment. Approximately 90% of this equipment is field-installed with many joints and fittings, which are prone to leaking fluorocarbon refrigerants[8,33]. Even with the complete implementation of BEPs globally, the release rates can still reach up to 11% (Supplementary Table 13). The mitigation of fluorocarbon emissions from the use stage in the ICR sector holds immense importance but remains extremely challenging.

Geographically, China, other A5 parties, and North America are expected to contribute 47%, 37%, and 11% to emission reductions, respectively. Compared with non-A5 parties, there is substantial mitigation potential from A5 parties. Taking China as an example, the cumulative GWP-weighed emissions are projected to decrease from 8.3 (±0.7) Gt CO_2e in the BAU to 3.5 (±0.4) Gt CO_2e in the S4 scenario. Approximately 45% of the reduction is expected to be attributable to
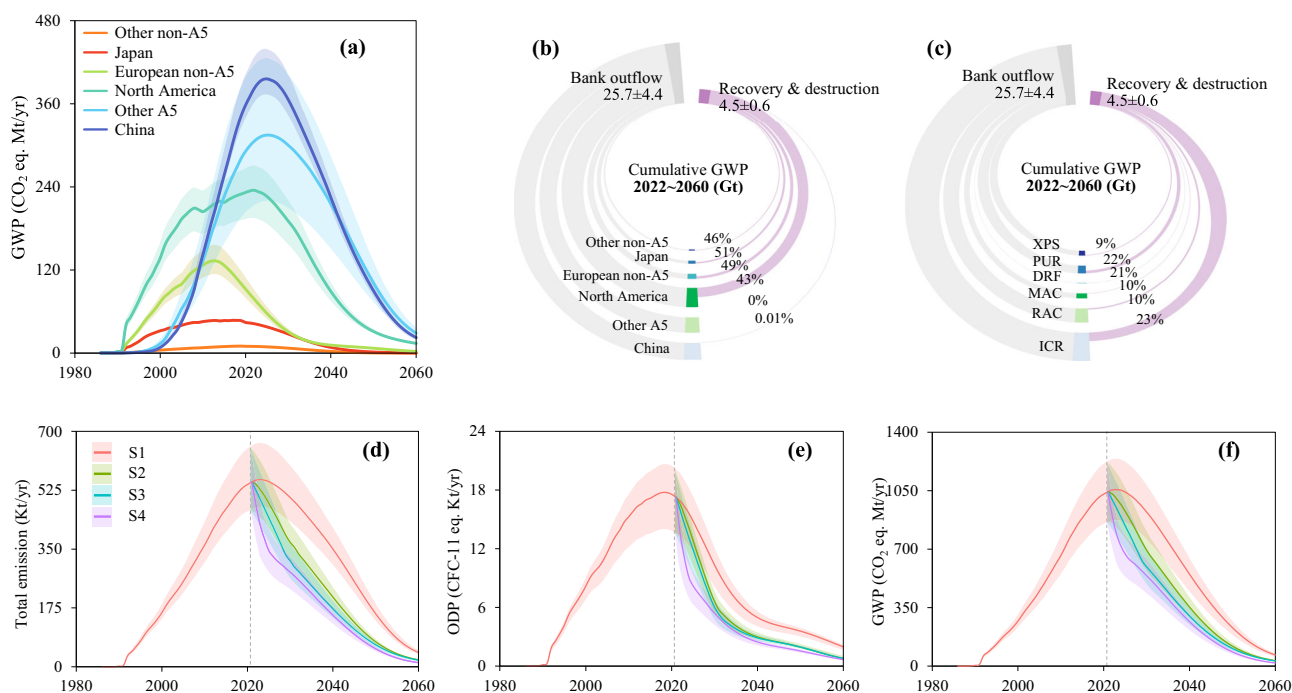

Fig. 2 | Abatement potential of mass emissions and global warming potential (GWP) and ozone depleting potential (ODP)-weighted emissions of the two fluorocarbon categories, under scenario-based analysis. a Annual GWP-weighted emissions of fluorocarbons in each geographic area under the business-as-usual (BAU, S1) scenario, from 1986 to 2060. **b, c** Cumulative GWP-weighted emission and mitigation via recovery and destruction actions by region and by sector, under the BAU scenario from 2022 to 2060. A5 parties include China and other A5, while non-A5 parties include Japan, North America (Canada and the USA only), European non-A5 and other non-A5 parties. End-use sectors include domestic refrigerator and freezer (DRF), room air conditioner (RAC), mobile air conditioner (MAC), industrial and commercial refrigeration (ICR), polyurethane rigid (PUR) foam, and extruded polystyrene (XPS) foam. **d–f** Mass emissions, ODP-weighted emissions and GWP-weighted emissions and their abatement potential of the two fluorocarbon categories under various scenarios from 1986 to 2060; 2021 served as the benchmark year. Under the BAU scenario, the global abatement practices between 2022 and 2060 will remain at the same level as that in 2021. Under Scenarios 2 (S2) and 3 (S3), Best Environmental Practices (BEPs) for emissions abatement will be partially applied in A5 parties between 2022 and 2060. S2 focuses on the end-of-life (EoL) stage, while S3 covers the use and EoL stages. Under Scenario 4 (S4), BEPs will be fully applied globally for use and EoL stages starting in 2023.

the RAC sector, followed by the ICR (32%) and MAC (10%) sectors. Similarly, the cumulative GWP can be decreased from 7.5 (±2.2) Gt CO₂e in the BUA scenario to 3.9 (±1.2) Gt CO₂e in the S4 scenario in other A5 parties. The ICR and RAC sectors are expected to become major contributors (41% and 39%, respectively), followed by the MAC sector (10%). In North America, the cumulative GWP will decrease from 4.0 (±0.6) Gt CO₂e in the BUA scenario to 3.0 (±0.5) Gt CO₂e in the S4 scenario. The ICR and XPS foam sectors are expected to be the primary contributors. If analyzed by the life cycle stage, sound management and recovery of scrap fluorocarbons at the EoL stage is expected to contribute 75% of the total emission reduction. However, addressing fluorocarbon emissions at the use stage remains a significant challenge.

Comparative analysis of HCFC mass emissions

In Figs. 3a–g, the curve graphs show the comparison analysis of the mass emissions of fluorocarbons between our estimates in the BAU scenario and those of previous studies using data compiled from atmospheric monitoring (top-down method)[19,25–29] or statistical data on production and consumption (bottom-up method)[19–21,36–38]. Both the multiple purposes of fluorocarbon applications and the uncertainties of consumption data and parameters resulted in moderate differences in HCFCs but only minor differences in HFCs between this study and other studies.

Our analysis indicates that HCFC-22 emissions from refrigerant-related equipment and foam products accounted for 60% of the emissions inferred from the observed mixing ratios in 2004[25] and increased to 70% in 2020[29] (Fig. 3a). These gaps were narrowed when comparing our findings with those of Lickley et al. (2020)[19] who applied the Bayesian probabilistic model. The discrepancies between our study and previous studies can primarily be attributed to the exclusion of HCFC-22 emissions from production, as feedstock, and in other applications, such as those used in aerosols with instantaneous emission characteristics[8,29]. According to Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) statistical data, approximately 12% of HCFC-22 was used in instantaneous emission applications during 1986–2003[37]. Feedstock-related HCFC-22 emissions account for 4–8% of global emissions[29]. Our estimations indicate that HCFC-22 emissions reached their peak in 2018. Subsequently, emissions declined noticeably from 2020 onward. Our emission trends align well with those derived from the HCFC-22 observational measurements provided by the World Meteorological Organization (WMO) (2022)[29]. However, our findings suggest that the downward trend in HCFC-22 emissions will decelerate from the 2040 s onward, which can be mainly attributed to a substantial proportion of HCFC-22 banks present in XPS foam products. These HCFC-22 banks are expected to reach their decommissioning peak in the late 2040 s in our BAU scenario (Fig. 3a and Supplementary Fig. 14).

For HCFC-141b and HCFC-142b, the mean values of our estimates from closed-cell foams accounted for 60% and 66%, respectively, of the emissions covering all emission sources inferred from the observed mixing ratios in 2020 (Fig. 3b, c)[29]. In addition, the disparity in emission estimates stems from the uncertainties in the consumption data. The sum of available regional sales data from FTOC series reports[39,40], which are the main data sources used in our model, is lower than the sales volumes from AFEAS statistics[37]. For example, based on AFEAS statistics, 1200 Kt of HCFC-141b and 500 Kt of HCFC-142b were produced and sold between 1986 and 2003, which are 20–30% higher than the FTOC statistics[37,39,40]. Moreover, feedstock-related HCFC-142b emissions account for 17–33% of global emissions[29]. Improving the accuracy of data on fluorocarbon consumption in various applications can benefit efforts to reconcile discrepancies between emissions calculated using bottom-up and top-down methods.

Our estimates captured the decreased trend in HCFC-141b emissions as the global decrease in HCFC-141b consumption around 2000[19,25–28]. However, we did not observe a temporary decline in HCFC-141b emissions from foam products during 2013–2016[19,28,29]. Our estimations reveal a decreasing trend in HCFC-141b emissions from closed-cell foams starting around 2023, which aligns with the decommissioning trend observed in PUR foams containing HCFC-141b used in appliances (Fig. 3b and Supplementary Fig. 14). However, this decreasing trend will change when PUR foams containing HCFC-141b used in the construction industry gradually reach their decommissioning peak. This phenomenon, which results from the coexistence of short- (e.g., appliance foams) and long-lifespan products (e.g., construction insulation foams), agrees with the findings of a previous study conducted by SKM Enviros[41].

Our estimates on HCFC-142b also captured the decreasing trend in emissions since 2008 as the decline in global consumption, albeit with a smoother trajectory than that in other studies[19,25–27] (Fig. 3c and Supplementary Fig. 14). The declining emissions observed in our study exhibit a magnitude that aligns well with the findings of Lickley et al.[19] after 2015. However, our results indicate that this decreasing trend will change from around 2026, with an increase in emissions during the EoL stage. In our BAU scenario, HCFC-142b emissions are projected to peak again around 2046, which coincides with the decommissioning trend observed in XPS foams containing HCFC-142b. Thereafter, the overall emissions are expected to decline again.

Our estimation model is similar to that outlined in United Nations Environment Programme Technology and Economic Assessment Panel (TEAP)[42]. We also simulated the emissions of HCFC-141b and HCFC-142b from closed-cell foam products using the parameters in "Appendix 4: Foam model assumptions" of TEAP[42] (Supplementary Discussion and Fig. 15). Similar to our estimates, the results obtained using the parameters in TEAP (2021) effectively captured the early declining trends in HCFC-141b and HCFC-142b emissions as a decrease in global consumption; however, they also failed to reveal the declining trend in HCFC-141b emissions during 2013–2016[19,28,29]. Our estimation incorporates various emission factors for the EoL treatment of foam products in different regions (Supplementary Methods). However, the TEAP[42] assumes uniform emission factors during the EoL stage for all regions, thereby ignoring a future increase in HCFC-142b emissions. Regarding HCFC-141b, in addition to emission factors, other parameters, particularly those related to lifespan distributions, can influence future increasing trends in emissions. To improve accuracy in forecasting fluorocarbon emissions, further investigation is required for emission characteristics and lifespan distributions of foam products.

Comparative analysis of HFC emissions

HFC-32 has been used primarily as a refrigerant in air conditioning systems[29]. Historical estimates of HFC-32 mass emissions in this study aligned well with those inferred from atmospheric observations[21,25–27,29] (Fig. 3d). HFC-125 has been used primarily as a refrigerant blend and for fire suppression[29]. The minor differences (gaps) for HFC-125 mass emissions in this study and those inferred from atmospheric observations (Fig. 3e) can primarily be attributed to the uncertainties of HFC consumption and the limited inclusion of HFC blends in this study (Table 1 in Method Section). From 2012 onward, within the error range, our estimation of HFC-125 mass emissions aligned well with the inferred emissions[21,25–27,29]. A similar trend and reasoning can be observed for HFC-143a mass emissions (Fig. 3g). HFC-134a can be used in other HFC refrigerant blends beyond HFC-404a and HFC-407c and in other applications such as aerosols, which were excluded from this study. These factors can account for the disparity between our estimations of HFC-134a mass emissions and those inferred from observations (Fig. 3f).

A few non-A5 parties have released their national or regional reports on non-CO₂ GHG emissions, including fluorocarbons, in the past decades[13–15]. Our estimates for HCFC and HFC emissions are comparable with these reports (Supplementary Discussion and
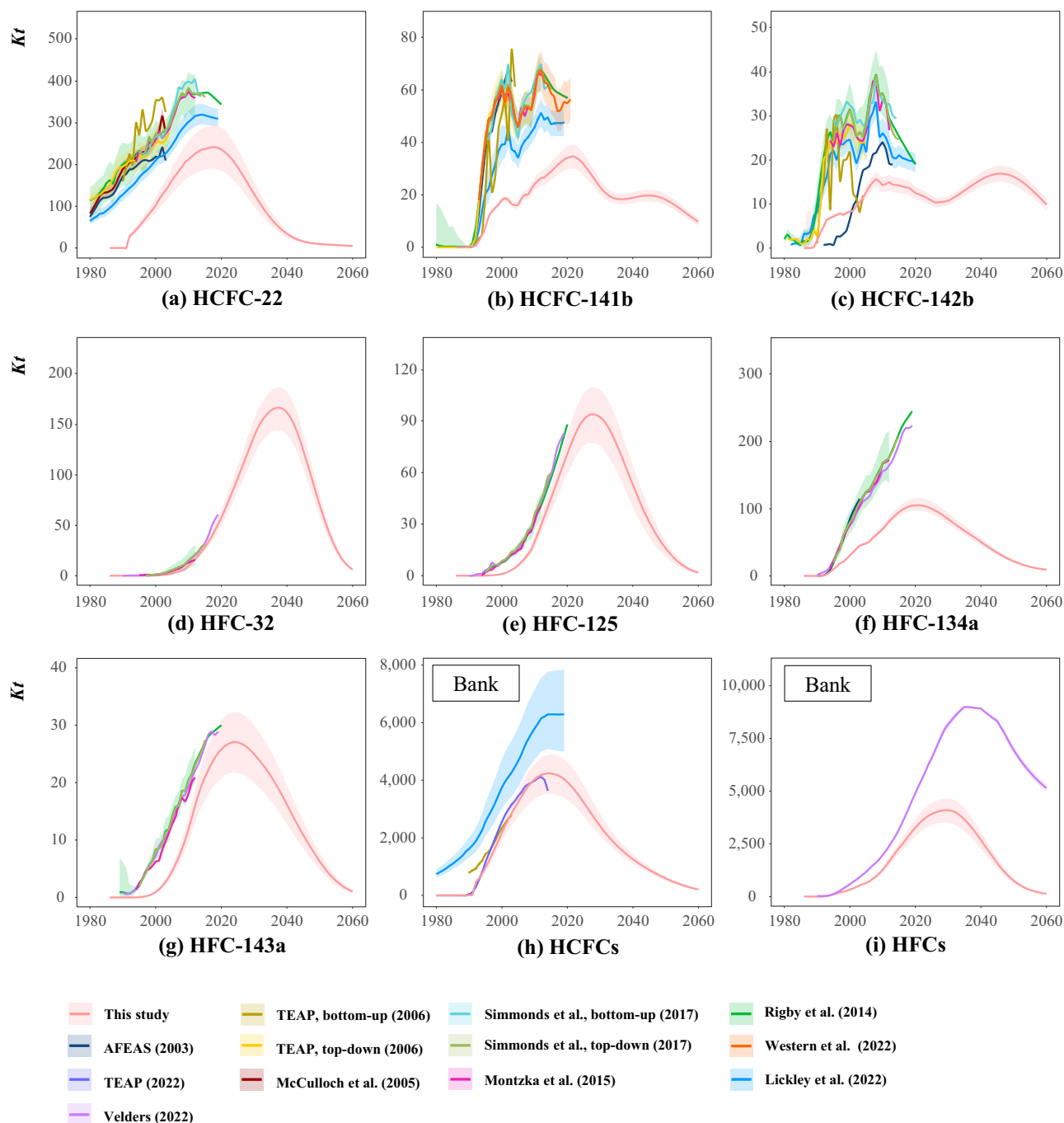
Fig. 3 | Comparisons of mass emission estimates of the fluorocarbons between our model in business-as-usual scenario and previous studies. a–g Comparisons of the estimated mass emissions of fluorocarbons from the findings of United Nations Environment Programme Technology and Economic Assessment Panel (TEAP)[36], Rigby et al.[25], Velders et al.[21], Montzka et al.[26], Simmonds et al.[27], and Western et al.[28] based on measurement data from atmospheric monitoring; estimates of Lickley et al.[19] based on the Bayesian probabilistic model; estimates of Alternative Fluorocarbons Environmental Acceptability Study (AFEAS)[37], TEAP[36], TEAP[38], and Simmonds et al.[27] based on the aggregated bottom-up production and consumption data for fluorocarbons; **h** comparisons of hydrochlorofluorocarbon (HCFC) banks between our model and previous work by TEAP[36], TEAP[38] and Lickley et al.[19]; **i** comparisons of hydrofluorocarbon (HFC) banks between our model and previous work by Velders et al.[21].

Supplementary Figs. 16, 17). WMO[29] reported the growth in the gap between the reported total GWP-weight emissions of HFCs by Annex I countries (listed in Supplementary Table 16, primarily non-A5 parties as listed in Supplementary Table 4) to the United Nations Framework Convention on Climate Change and global estimates derived from atmospheric data. Our estimations are in line with this trend and predict a continued decline in emission contributions from non-A5 parties in the future (Supplementary Fig. 18).

Comparative analysis of HCFC banks
Our estimate of HCFC-22 banks is comparable to the results obtained from TEAP[36] and TEAP[38] but slightly lower than that provided by Lickley et al.[19] (Fig. 3h). This discrepancy can be attributed to the differences in consumption data between our study and Lickley et al.'s[19] study, and the data used in Lickley's model[19] exceed the reported production by 6–13% (828–1712 Kt). Our estimates of HCFC-141b and HCFC-142b banks align well with those of TEAP[36] and TEAP[38]; within the

Table 1 | End-use sectors and fluorocarbons considered in this study (tick mark)

Fluorocarbon	DRF	RAC	ICR	MAC	PUR	XPS
HCFC-22		√	√			√
HCFC-141b					√	
HCFC-142b						√
HFC-32		√	√			
HFC-134a	√		√	√	√	√
HFC-410a		√	√			
HFC-404a			√			
HFC-407c		√	√			
HFC-507a			√			

HFC-410a (50%/50% HFC-32/HFC-125, by mass), HFC-404a (44%/52%/4% HFC-125/HFC-143/HFC-134a, by mass), HFC-407c (23%/25%/52% HFC-32/HFC-125/HFC-134a, by mass), and HFC-507a (50%/50% HFC-125/HFC-143a, by mass).

DRF domestic refrigerator and freezer, *RAC* room air conditioner, *MAC* mobile air conditioner, *ICR* industrial and commercial refrigeration, *PUR* polyurethane rigid foam, *XPS* extruded polystyrene foam.

margin of error, these estimates are consistent with the findings reported by Lickley et al.[19].

Comparative analysis of HFC banks

Our estimates of these HFC banks account for approximately 80% of the results presented by Velders et al.[21] prior to 2021 (Fig. 3i). The disparity between our bank estimates and those by Velders et al.[21] can mainly be attributed to variations in the application scopes of these HFC chemicals (Table 1). Specifically, Velders et al.[20,21] included all application fields of these HFC chemicals to conduct a more comprehensive assessment of the efficacy of the Kigali Amendment. In contrast, we focused only on refrigerant- or blowing agent-related applications, considering prevalent HFCs and their blends to explore emission mitigation pathways for banked fluorocarbons.

Regarding the projection of HFC banks, the significant divergence of results between this study and Velders et al.[21] may arise from variations in the application scopes of these HFCs (Table 1), distinct estimation models, and disparities in the projection of future consumption patterns. Velder et al.[21] assumed that influenced by the Kigali Amendment, trends in fluorocarbon consumption based on GDP and population growth follow either Shared Socioeconomic Pathway 5 (SSP5) or SSP3. Their projection of HFC banks peaks at approximately 9000 Kt, which is significantly larger than our projection (Supplementary Fig. 19) and the peaks of the previously estimated HCFC banks[19,38]. For our projection, we mainly focused on refrigerant-related and blowing agent-related fluorocarbon applications. We relied on historical data and assumed that HFC consumption in non-A5 and A5 parties aligned well with their corresponding national or regional plans, if any. In cases where such plans are unavailable or not accessible, these countries are expected to strictly adhere to the phase-down schedule required by the Montreal Protocol and its amendments and adjustments (Method and Supplementary Methods). Compared with the HFC consumption projected on the basis of GDP and population growth under SSPs by Velders et al.[21], our projection anticipates a lower consumption level.

As a reminder, emissions from banked fluorocarbons may not be exclusively related to the lack of regulations or mandatory BEPs in some countries. External damage from natural or man-made hazards can cause these releases[43,44]. Given the intrinsic randomness of such events, this may add further uncertainty (even if not quantifiable) to the analysis.

Implications for fluorocarbon management

The management and control of fluorocarbons need to cover all life cycle stages. Sound management programs for E-waste exist in most

non-A5 parties[45], and these have been extended to cover refrigerant management as well. However, achieving effective implementation of such activities and their extension to include refrigerants in most A5 parties requires the development of relevant legal systems and stringent enforcement and supervision. All stakeholders should share the burden and actively participate in fluorocarbon emission reduction. Unintentional discharge of refrigerants should be avoided during servicing, refilling, and EoL treatment. In the EoL stage, implementing BEPs for sound management and recovery of scrap fluorocarbons can significantly mitigate emissions. However, during the use stage, in addition to regular leakage check and repair activities, groundbreaking innovations are required, especially for the ICR sector, which accounts for a significant number of refrigerants, resulting in high emissions.

Methods
Scope and data

Table 1 presents the two fluorocarbon categories and end-use sectors defined in this study. We included three ODSs (HCFC-22, HCFC-141b, and HCFC-142b), four major HFCs (HFC-32, HFC-134a, HFC-125, and HFC-143), and their blends (HFC-404a, HFC-407c, HFC-410a, and HFC-507a). The global consumption masses of HCFC-22, HCFC-141b, and HCFC-142b account for approximately 98% of the overall HCFC consumption[37,46], and the consumption masses of HFC-32, HFC-125, HFC-134a, and HFC-143a account for 87% of the total HFC consumption[46]. Therefore, a high degree of representativeness was observed for the selected fluorocarbon compounds included in this study. We excluded other less prevalent HCFCs (such as HCFC-123 and HCFC-124) and HFCs (such as HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, and HFC-365mfc) because of their minor contribution to the overall dataset[46] and limited availability of regional consumption data. To avoid the uncertainty associated with the long-term development of refrigerants and blowing agents, other low-GWP HFCs and their blends and substitutes were excluded from this study. HFC substitutes, such as hydrocarbons, inorganic compounds (such as ammonia, nitrogen, and carbon dioxide), and unsaturated organic compounds (HFO-1234yf), were excluded because of their extremely low GWP values[8].

In terms of end-use sectors, we have covered most of the durable equipment and products in which these fluorocarbons are used as refrigerants or closed-cell foam. Refrigerant-related applications were further divided into the DRF, RAC, MAC, and ICR sectors. Foam-related applications were further divided into PUR and XPS foam sectors. In terms of region, the Montreal Protocol classifies global countries as A5 or non-A5 parties. We considered this differentiation and the market characteristics of world countries and eventually divided them into six geographical regions: China, Japan, North America (including Canada and the United States only), European non-A5 parties, other non-A5 parties, and other A5 parties. China and other A5 parties are defined as A5 parties, whereas the remaining countries are defined as non-A5 parties in the Montreal Protocol. As of April 2024, the Kigali Amendment was ratified by 159 countries, including nations with significant contributions to global HFC production and consumption. More details can be found in Supplementary Methods.

We performed emission accounting based on the Tier 2a Emission-factor approach of the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories[31,32]. Following the scope defined above, the emissions of each type of HCFC or HFC were calculated by different sectors, regions, and life cycle stages from the manufacturing, use, and EoL phases of products or equipment containing these chemicals.

The production and consumption of fluorocarbons in countries were assumed to be subject to the Montreal Protocol, the Kigali Amendment, and their national or regional strategies within the scope of this study. The data sources and calculation processes are detailed in Supplementary Methods. In short, we first collected time-series sales statistics of new equipment or products by sector and country or region.

Next, we determined the time-series consumption of HCFCs and HFCs in non-A5 and A5 parties following the available national or regional plans. When such plans were not available, we followed the schedule of phase-out requirements set by the Kigali Amendment and other amendments under the Montreal Protocol. Note that this study considers only reported sales of equipment and products using HCFCs and HFCs.

Dynamic material flow analysis modeling

The stocks and flows of fluorocarbon-containing products and equipment were estimated using a dynamic material flow analysis (MFA) model, which combined the statistics on new sales volume of fluorocarbon-containing products and equipment with their estimated lifespans. A remaining rate function was used to determine their lifespans[47,48], and a Weibull distribution was assumed for the lifespan distribution, as has been extensively done in previous studies[49–51] and is shown in Eq. (1).

$$f(y,t) = \exp\left\{-\left(\frac{t+0.5}{u}\right)^{\beta}\right\}, \tag{1}$$

where $f(y,t)$ denotes the remaining rate of the new sales of product or equipment in year y; t represents the product or equipment age; β represents the shape parameter $(\beta > 0)$; u represents the scale parameter $(u > 0)$. The quantity of product and equipment in the use stage and EoL stage and the corresponding mass of fluorocarbon compounds in each sector within each region can be determined using Eqs. (2)–(7):

$$N_{use}(y,t) = N_{new}(y,0) \times f(y,t), \tag{2}$$

$$N_{EoL}(y,t) = N_{use}(y,t) - N_{use}(y,t+1), \tag{3}$$

$$Total\_N_{use}(Y) = \sum_{y}^{Y} N_{new}(y,t=Y-y), \tag{4}$$

$$Total\_N_{EoL}(Y) = \sum_{y}^{Y} N_{EoL}(y,t=Y-y), \tag{5}$$

$$M_{use}(Y) = Total\_N_{use}(Y) \times m_{new}(Y) \times q, \tag{6}$$

$$M_{EoL}(Y) = Total\_N_{EoL}(Y) \times m_{new}(Y) \times \rho, \tag{7}$$

where Y represents the target year for calculating fluorocarbon emissions; y represents the sales year of the product or equipment charged with the fluorocarbon compound; $N_{new}(y,0)$ denotes the sales volume of new products or equipment in year y; $N_{use}(y,t)$ denotes the volume of in-use products or equipment sold in year y with age t; $N_{EoL}(y,t)$ denotes the volume of EoL product or equipment sold in year y with age t; $TotalN_{use}(Y)$ denotes the total volume of in-use product or

equipment in year Y; $TotalN_{EoL}(Y)$ denotes the total volume of EoL product or equipment in year Y; $m_{new}(Y)$ denotes the average charge mass of fluorocarbons per product or equipment in year Y; $M_{use}(Y)$ and $M_{EoL}(Y)$ denote the masses of each fluorocarbon in product or equipment use and EoL stages, respectively, at year Y; q and ρ denote the proportions of refrigerant charge remaining in the product or equipment use and EoL stages, respectively, in which leakage and refill during the use stage are covered.

For each compound of HCFC or HFC, the emission mass from each sector was derived on the basis of its annual mass in the product or equipment during the manufacturing, use, and EoL treatment stages. Following the Tier 2a method of the IPCC Guidelines for National Greenhouse Gas Inventories[31,32], as used in previous studies and national reports[11,17,24,33], we can estimate and project the historical and future emissions of HCFCs and HFCs, as shown in Eq. (8).

$$\begin{aligned} E_{total}(Y) &= E_{man}(Y) + E_{use}(Y) + E_{EoL}(Y) \\ &= N_{new}(Y) \times m_{new}(Y) \times Ef_{man}(Y) + M_{use}(Y) \\ &\quad \times Ef_{use}(Y) + M_{EoL}(Y) \times (1 - \gamma_{EoL}(Y)), \end{aligned} \tag{8}$$

where $E_{total}(Y)$ denotes the total emissions of each HCFC or HFC from a target sector in year Y; $E_{man}(Y)$, $E_{use}(Y)$, and $E_{EoL}(Y)$ denote the mass emissions of each fluorocarbon from the manufacturing, use, and EoL stages of product or equipment in the target sector, respectively, at year Y; $N_{new}(Y)$ denotes the new sales of product or equipment in year Y and equals $N_{new}(y,0)$ in Eq. (2) when Y equals y; $Ef_{man}(Y)$ and $Ef_{use}(Y)$ denote the annual emission factors of each chemical during the life cycle stages of product or equipment manufacturing and use, respectively; $\gamma_{EoL}(Y)$ denotes the recovery efficiency of each chemical during product or equipment EoL treatment. The parameters are described in more detail in Supplementary Methods.

Scenario setting for emission abatement potential

Fluorocarbons may remain in the EoL stage for durable equipment[31,32]. Although sound management practices for scrap fluorocarbons have been established in a few non-A5 parties, most of these chemicals in A5 parties are released into the atmosphere[16]. To evaluate the abatement potential of emissions into the future, we developed scenarios for applying BEPs, which are optimal service and leakage-prevention practices during the use stage, along with sound recovery and destruction practices during the EoL stage (Table 2). Details are provided in Supplementary Methods.

We assume the alignment of future fluorocarbon consumption in non-A5 and A5 parties with their respective national or regional plans, such as Japan's "Act on Rational Use and Proper Management of Fluorocarbons"[13] or the European Union's F-gas regulation[14]. In cases where national or regional strategies are absent or inaccessible, the parties involved are expected to adhere to the phase-down schedule required by the Montreal Protocol and its amendments and adjustments. These consumption estimates apply to each scenario. Scenario 1 (S1) is a BAU scenario, with 2021 as the baseline, where HCFC and HFC

Table 2 | Scenario settings for applying Best Environmental Practices (BEPs) to curb fluorocarbon emissions between 2022 and 2060

Scenario	Targeted sector	Targeted geographic area	Targeted life cycle stage	Targeted BEPs
S1 (Business-as-usual)	All covered	Both A5 and non-A5	Use and EoL stages	Remaining the same as 2021 (BEPs applied only in several non-A5 nations)
S2 (Moderate)	All covered	A5 only	EoL stage	Applying BEPs by linearly increasing to 50%–100%
S3 (Super)	All covered	A5 only	Use and EoL stages	Applying BEPs by linearly increasing to 50%–100%
S4 (Optimal)	All covered	Both A5 and non-A5	Use and EoL stages	Fully applying BEPs

Targeted sectors include domestic refrigerator and freezer (DRF), room air conditioner (RAC), mobile air conditioner (MAC), industrial and commercial refrigeration (ICR), polyurethane rigid (PUR) foam, and extruded polystyrene (XPS) foam. Targeted geographic areas cover Article 5 (A5) and non-Article 5 (non-A5) parties under the Montreal Protocol, and the A5 parties include China and other A5 parties, while the non-A5 parties include Japan, North America (Canada and the USA only), European non-A5 and other non-A5 parties. Targeted life cycle stages include manufacturing, use, and end-of life (EoL).

emission parameters during use and EoL treatment remain the same until 2060. Some developed countries or regions, such as Japan, the United States, and the European Union, have partially implemented BEPs. In the BAU scenario, continued implementation of these BEPs will be assumed, with the emission factors or recovery efficiencies for HCFCs or HFCs in either non-A5 or A5 parties expected to remain unchanged from 2021 to 2060. Scenarios 2 (S2), 3(S3), and 4 (S4) are assumed to be mitigation scenarios with different degrees of BEP implementation in different geographic areas and stages. In S4, BEPs will be fully applied globally starting in 2023, covering the use and EoL stages. This scenario represents the global maximum abatement potential of emissions. Scenarios S2 and S3 are assumed to apply BEPs up to the extent of 50%–100% in A5 parties starting in 2030. S2 focuses on applying BEPs only in the EoL stage, whereas S3 covers both the use and EoL stages. S2 and S3 probably represent operable scenarios for fluorocarbon mitigation. Supplementary Table 13 summarizes the implementation rates of BEPs and associated parameters. Parameter settings determine the effects of conducting leakage checks regularly or seldom during the use stage. Through the development of appropriate parameters, various practices for preventing emissions may yield varying effects on fluorocarbons used as refrigerants or foaming agents.

Uncertainties and sensitivity analysis

There are uncertainties regarding the estimation and projection of fluorocarbon emissions. First, fluorocarbon-related consumption data, including product or equipment sales, refrigerant charge mass, and refrigerant type proportions, can result in uncertainties (Supplementary Table 14). Second, some parameters used in this study were assumed to be constant over time, such as the emission factors, scale and shape parameters of the Weibull distribution for equipment lifespans, and proportions of refrigerants remaining in the product or equipment use and EoL stages. These constant parameters suggest good estimates but still contain uncertainties. Third, some chemicals were excluded from this study, such as other less prevalent HFC blends used as refrigerants. Considering the uncertainty of some of these key parameters, we show the uncertainties of HCFC and HFC emissions from the ICR and RAC sectors (Supplementary Tables 17, 18).

Data availability

Raw data used to produce all of the figures in the main text and supplementary information are provided in the Source Data file. Source data are provided with this paper.

References

1. Berwald, J. One overlooked way to fight climate change? Dispose of old CFCs. National Geographic. https://www.nationalgeographic.com/environment/article/disposing-old-cfcs-refrigerants-reduces-climate-change-greenhouse-gases-cheaply (2019).
2. Barnes, P. W. et al. Ultraviolet radiation, climate change and prospects for a sustainable future. *Nat. Sustain.* **2**, 569–579 (2019).
3. Chipperfield, M. P. et al. Renewed and emerging concerns over the production and emission of ozone-depleting substances. *Nat. Rev. Earth Env.* **1**, 251–263 (2020).
4. Young, P. J. et al. The Montreal Protocol protects the terrestrial carbon sink. *Nature* **596**, 384–388 (2021).
5. Velders, G. J. et al. Climate change. Preserving Montreal Protocol climate benefits by limiting HFCs. *Science* **335**, 922–923 (2012).
6. Powell, R. L. CFC phase-out: have we met the challenge? *J. Fluor. Chem.* **114**, 237–250 (2002).
7. World Meteorological Organization (WMO). *Scientific Assessment of Ozone Depletion: 2018*. Global Ozone Research and Monitoring Project-Report No. 58 (World Meteorological Organization, 2018).
8. United Nations Environment Programme (UNEP). Refrigeration, Air Conditioning and Heat Pumps Technical Option Committee (RTOC): 2018 Assessment report. https://ozone.unep.org/sites/default/files/2019-04/RTOC-assessment-report-2018_0.pdf (2018).
9. Velders, G. J. et al. The large contribution of projected HFC emissions to future climate forcing. *Proc. Natl Acad. Sci. USA.* **106**, 10949–10954 (2009).
10. China Association of Fluorine and Silicone Industry (CAFSI). Development status and prospect of fluorocarbon chemicals in China. http://sif.org.cn/article/922 (2023).
11. Fang, X. et al. Changes in emissions of ozone-depleting substances from China due to implementation of the Montreal Protocol. *Environ. Sci. Technol.* **52**, 11359–11366 (2018).
12. United Nations Environment Programme (UNEP). *Decision XIX/6: Adjustments to the Montreal Protocol with regard to Annex C, Group I, substances (hydrochlorofluorocarbons), Section 4* (UNEP, 2007).
13. Japanese Ministry of Justice. *Act on Rational Use and Appropriate Management of Fluorocarbons* (Japanese Ministry of Justice, 2022).
14. European Commission (EC). EU legislation to control F-gases, https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/eu-legislation-control-f-gases_en#mac-directive (2015).
15. United States Environmental Protection Agency (US EPA). Greenhouse Gas Reporting Program (GHGRP) Fluorinated Chemicals. https://www.epa.gov/ghgreporting/ghgrp-fluorinated-chemicals (2022).
16. Duan, H. et al. Chilling prospect: climate change effects of mismanaged refrigerants in China. *Environ. Sci. Technol.* **52**, 6350–6356 (2018).
17. Li, Z. et al. Estimated HCFC-22 emissions for 1990–2050 in China and the increasing contribution to global emissions. *Atmos. Environ.* **132**, 77–84 (2016).
18. Lickley, M. et al. Quantifying contributions of chlorofluorocarbon banks to emissions and impacts on the ozone layer and climate. *Nat. Commun.* **11**, 1380 (2020).
19. Lickley, M. et al. Bayesian assessment of chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC) and halon banks suggest large reservoirs still present in old equipment. *Atmos. Chem. Phys.* **22**, 11125–11136 (2022).
20. Velders, G. J. et al. Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmos. Environ.* **123**, 200–209 (2015).
21. Velders, G. J. et al. Projections of hydrofluorocarbon (HFC) emissions and the resulting global warming based on recent trends in observed abundances and current policies. *Atmos. Chem. Phys.* **22**, 6087–6101 (2022).
22. Fang, X. et al. Hydrofluorocarbon (HFC) emissions in China: an inventory for 2005–2013 and projections to 2050. *Environ. Sci. Technol.* **50**, 2027–2034 (2016).
23. Flerlage, H., Velders, G. J. & Boer, J. D. A review of bottom-up and top-down emission estimates of hydrofluorocarbons (HFCs) in different parts of the world. *Chemosphere* **6**, 131208 (2021).
24. Bai, F. et al. Pathway and Cost-Benefit Analysis to Achieve China's Zero Hydrofluorocarbon Emissions. *Environ. Sci. Technol.* **57**, 6474–6484 (2023).
25. Rigby, M. et al. Recent and future trends in synthetic greenhouse gas radiative forcing. *Geophys. Res. Lett.* **41**, 2623–2630 (2014).
26. Montzka, S. A. et al. Recent Trends in Global Emissions of Hydrochlorofluorocarbons and Hydrofluorocarbons: Reflecting on the 2007 Adjustments to the Montreal Protocol. *J. Phys. Chem. A* **119**, 4439–4449 (2015).
27. Simmonds, P. G. et al. Changing trends and emissions of hydrochlorofluorocarbons (HCFCs) and their hydrofluorocarbon (HFCs) replacements. *Atmos. Chem. Phys.* **17**, 4641–4655 (2017).
28. Western, L. M. et al. A renewed rise in global HCFC-141b emissions between 2017–2021. *Atmos. Chem. Phys.* **22**, 9601–9616 (2022).

29. World Meteorological Organization (WMO). *Scientific Assessment of Ozone Depletion: 2022*. Ozone Research and Monitoring – GAW Report No. 278 (WMO, 2023).

30. Friedlingstein, P. et al. Global Carbon Budget 2022. *Earth Syst. Sci. Data* **14**, 4811–4900 (2022).

31. Intergovernmental Panel on Climate Change (IPCC). *IPCC Guidelines for National Greenhouse Gas Inventories*, vol. 3. Industrial Process and Product Use (IPCC, 2006).

32. Intergovernmental Panel on Climate Change (IPCC). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, vol. 3. Industrial Process and Product Use (IPCC, 2019).

33. Japan Ministry of Economy, Trade and Industry (Japan METI). Documents pertaining to methods for estimating discharge (in Japanese) (2009).

34. Nomura Research Institute, Ltd. (NRI). Chemical substance safety measures: report on the actual condition of the leakage amount in the use of refrigerators for business use (2021).

35. Japan Association for Electric Home Appliances (AEHA). Annual recycling report for household electric appliance. https://www.aeha-kadenrecycle.com/effort/#a_07 (2022).

36. United Nations Environment Programme (UNEP). *Technology and Economic Assessment Panel (TEAP): Task Force on Emissions Discrepancies Report, 2006*. Nairobi, Kenya (UNEP, 2006).

37. Alternative Fluorocarbons Environmental Acceptability Study (AFEAS). Production and atmospheric release data through 2003. https://agage.mit.edu/data/afeas-data (2003).

38. United Nations Environment Programme (UNEP). Technology and Economic Assessment Panel (TEAP). *2022 Assessment Report*. UNEP Nairobi, Ozone Secretariat (UNEP, 2023).

39. United Nations Environment Programme (UNEP). *Report of the Rigid and Flexible Foams Technical Options Committee (FTOC)* (UNEP, 2018).

40. United Nations Environment Programme (UNEP). *Report of the Rigid and Flexible Foams Technical Options Committee (FTOC)* (UNEP, 2002).

41. SKM ENVIROS, Further Assessment of Policy Options for the Management and Destruction of Banks of ODS and F-Gases in the EU, Prepared for the European Commission. Final report, (SKM ENVIROS, 2012).

42. United Nations Environmental Programme (UNEP)/Technology and Environmental Assessment (TEAP) 2021: Decision XXXI/3 TEAP Task Force Report On Unexpected Emissions Of Trichlorofluoromethane (CFC-11) (Vol. 3), https://ozone.unep.org/system/files/documents/Final_TEAP-DecisionXXXI-3-TF-Unexpected-Emissions-of-CFC-11-may2021.docx (2021).

43. Saito, T. et al. Extraordinary halocarbon emissions initiated by the 2011 Tohoku earthquake. *Geophys. Res. Lett.* **42**, 2500–2507 (2015).

44. Filippo, R. et al. Global warming and ozone depletion potentials caused by emissions from HFC and CFC banks due structural damage. *Energ. Build.* **273**, 112385 (2022).

45. Li, J. & Xu, G. Circular economy towards zero waste and decarbonization. *Circular Econ.* **1**, 100002 (2022).

46. Bella M. *Current and Future HFC Demand by Sectors*. Workshop on HFC Management Bangkok, 20 April 2015. https://ozone.unep.org/meetings/workshop-hydrofluorocarbon-management-2015/introductory-presentations (2015).

47. Mueller, B. et al. Service lifetimes of mineral end uses. USGS Mineral Resources External 1507 Research Program Final Reports, Award 06HQGR0174 (2007).

48. Liu, H. et al. Dynamic stock, flow, and emissions of brominated flame retardants for vehicles in Japan. *J. Clean. Prod.* **232**, 910–924 (2019).

49. Wang, F. et al. Enhancing e-waste estimates: Improving data quality by multivariate Input–Output Analysis. *Waste Manage.* **33**, 2397–2407 (2013).

50. Oguchi, M. et al. Estimation of lifetime distributions and waste numbers of 23 types of electrical and electronic equipment. *J Japan Soc. Waste Manage. Experts* **17**, 50–60 (2006).

51. Oguchi, M. & Fuse, M. Regional and longitudinal estimation of product lifespan distribution: a case study for automobiles and a simplified estimation method. *Environ. Sci. Technol.* **49**, 1738–1743 (2015).

Acknowledgements

Author contributions

H.L., H.D., and J.Y conceptualized and designed the study. H.L. and H.D. conceived the paper, developed the model. H.L. and Y.M. collected the data and conducted the analysis. N.Z. drew the figures. H.D., N.Z., T.R.M., and G.L. contributed to the conceptual model development. R.M., M.X., J.L., and J.Y. enhanced scenario analysis discussions. H.L., H.D., N.Z., Y.M., G.L., T.R.M., R.M., M.X., J.L., and J.Y. contributed to discussing the results and writing the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41467-024-51113-2.

Correspondence and requests for materials should be addressed to Huabo Duan or Jiakuan Yang.

Peer review information *Nature Communications* thanks Rocco di Filippo, and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. A peer review file is available.

Reprints and permissions information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.