















Continuing industrial emissions are delaying the recovery of the stratospheric ozone layer

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Stefan Reimann ^{1,15} ✉, Luke M. Western ^{2,3}, Megan J. Lickley ^{4,5}, David Sherry ^{6,15}, John S. Daniel ⁷, Lambert J. M. Kuijpers ⁸, Stephen A. Montzka ⁹, Matthew Rigby ², Guus J. M. Velders ^{10,11}, Martin K. Vollmer ¹, Lukas Emmenegger ¹, Qing Liang ¹², Sunyoung Park ¹³ & Susan Solomon ¹⁴

The Montreal Protocol on Substances that Deplete the Ozone Layer has greatly restricted the global production and consumption of long-lived ozone-depleting substances (ODS). However, ODS used or consumed as feedstocks in the manufacture of other chemicals are excluded from restrictions. This exclusion was based on the assumption that emission rates of feedstocks were only 0.5% of the amount produced and that feedstock production would decline in the future, with remaining emissions too small to significantly affect the stratospheric ozone or its recovery. In sharp contrast, feedstock emissions are now assessed as being substantially higher (typically 3.6% of production), and feedstock production and use has been rising rather than falling. Here, scenarios in which feedstock-related ODS emissions continue at this current fraction of production, rather than the 0.5% reference case, are projected until 2100. Without additional measures, these elevated emissions could delay the recovery of the mid-latitude stratospheric ozone layer by 7 (6 – 11) years. Furthermore, limiting ODS feedstock emissions would also reduce their effect on direct radiative forcing and on climate change.

Under the 1987 Montreal Protocol and its amendments, the production and consumption of ODS with a high ozone-depletion potential (ODP) have been globally banned for emissive uses since 2010. This group of ODS includes chlorofluorocarbons (CFCs) and other long-lived chlorinated and brominated compounds. Hydrochlorofluorocarbons (HCFCs) were introduced as interim substitutes for ODS with a high ODP. They are also ODS but due to their smaller effect on ozone destruction, production for emissive uses is still permitted in very limited quantities until 2040 in developing countries defined under the Montreal Protocol.

In contrast, the production and consumption of ODS for feedstock applications (i.e. as chemical building blocks in the production of other chemical end products) has no restrictions under the Protocol. However, under Article 7 of the Protocol, countries are obliged to report their annual feedstock production and consumption to the United Nations Environment Programme (UNEP).

In the 1990 London Amendment, Parties were additionally urged to take steps to minimize emissions related to feedstocks. Consequently, the Technology and Economic Assessment Panel of the

¹Laboratory for Air Pollution/Environmental Technology, Empa, Dübendorf, Switzerland. ²School of Chemistry, University of Bristol, Bristol, UK. ³Center for Sustainability Science and Strategy, Massachusetts Institute of Technology, Cambridge, MA, USA. ⁴The Earth Commons, Georgetown University, Washington, DC, USA. ⁵Walsh School of Foreign Service, Georgetown University, Washington, DC, USA. ⁶Nolan Sherry & Associates Ltd, Surrey, UK. ⁷NOAA Chemical Sciences Laboratory, Boulder, CO, USA. ⁸A/gent b.v. Environmental Consultancy, Venlo, Netherlands. ⁹NOAA Global Monitoring Laboratory, Boulder, CO, USA. ¹⁰National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands. ¹¹Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Utrecht, the Netherlands. ¹²NASA Goddard Space Flight Center, Greenbelt, MD, USA. ¹³Kyungpook National University, School of Earth System Sciences, Department of Oceanography, Daegu, South Korea. ¹⁴Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA. ¹⁵These authors contributed equally: Stefan Reimann, David Sherry. ✉e-mail: stefan.reimann@empa.ch

inferred global emissions of substances used primarily as feedstocks suggest that the emitted fraction of production of these chemicals was higher than estimated during the 1990s^{4–8}, which underscores the potential benefits of limiting feedstock emissions, discussed for example by Andersen et al.⁹

Evidence that feedstock-related emissions are higher than expected is exemplified here by CCl₄. Following the 2010 phase-out of CCl₄ for emissive uses, annual CCl₄ emissions remained at a level of several tens of thousands of tonnes between 2010 and 2023^{7,10,11}. These emissions could not be reconciled by the sum of (a) a 0.5% emission rate from its production and use as a feedstock, (b) additional emissions of CCl₄ as a by-product in the production of PVC (polyvinyl chloride), and (c) losses from landfills and other legacy sites^{8,11,12}. To close this gap, higher losses from feedstock CCl₄ were proposed by Liang et al.¹¹, and Sherry et al.¹², and finally the emission factor was revised to be 4.3% of production^{8,12}. In a recent analysis¹³, this value was further split into 2% losses during the actual production and 2.3% from the use as feedstock. It should be emphasised that this higher emission factor was independently accompanied by a substantial increase in the use of CCl₄ as a feedstock of 4–5% per year between 2014 and 2024 (Fig. S2). This development was mainly caused by a continuously increasing production of CCl₄-dependent HFOs and HCFOs (Fig. 1), which are important fluorochemical substitutes for enabling the phase-down of HFCs with larger GWPs. In addition to CCl₄, also emissions of CFC-113/a, CFC-114/a and 1,1,1-trichloroethane (CH₃CCl₃) have been higher than expected in recent years^{4–6,8,10,14,15}. Because emissions from remaining banks of these substances should now be negligible, their ongoing emissions must primarily be related to losses from continued feedstock use or from by-product emissions (see Fig. 1 for pathways).

For feedstock chemicals other than CCl₄, emissions were estimated by Daniel and Reimann et al.⁸ to be 2–4%, based on the ratio of global emissions, derived from atmospheric measurements, against production reported to UNEP³. Subsequently, this top-down estimate was further substantiated at 3.6%¹³ using bottom-up data, which is a combination of emissions from production (2.5%), distribution (0.5%), and the conversion of the ODS feedstocks into the final product (0.6%). This emission fraction of 3.6% is used in this work as the default for the business-as-usual (BAU) scenario for ODS feedstocks (except CCl₄) over the period 2024–2100. This same value is also used for Halon-1301, because we consider that there is no conclusive evidence for the substantially higher value of 26% that has been discussed¹³. For CCl₄, the slightly higher emission rate of 4.3%, discussed above, is applied⁸. Finally, the emission rate of CFC-115, likely only emitted as a by-product from the manufacturing of HFC-125 (Fig. 1), is estimated at 0.8% (see Supplementary Information).

Starting in 2024, the BAU emissions scenario is compared with a low-emission scenario (LOW) and a zero-emissions scenario (ZERO). The LOW scenario assumes an emission rate of 0.5% relative to the production from 2024 onward, consistent with the value originally assessed from well-managed facilities in the 1990s. It is used to assess the impact of immediate compliance with those anticipated feedstock-abatement levels in contrast to the BAU scenario. The ZERO scenario is identical to the LOW scenario but assumes zero feedstock-related emissions from 2024 onward.

To project future trends in the production and consumption of ODS feedstocks from 2025 to 2100, historical production trends between 2014 and 2024 (Fig. S2) are combined with expected changes in specific feedstock applications (see Supplementary Information). This results in compound-specific growth rates (Table 1) that are projected into the future in three steps. First, for the next 10 years (2025–2034), second, until 2050 and, finally, with stable production quantities between 2050 and 2100 for all feedstock applications. In brief, the production and consumption of ODS feedstock chemicals to produce controlled HFCs (Fig. 1) is projected to decline in the late 2020s, related to the phase-down under the Kigali Amendment. On the

other hand, the production of HFOs, as important replacement compounds, is assumed to continue to increase at a rate similar to 2014–2024. These two opposing trends particularly influence the future production of CCl₄ and make the prediction of its long-term behaviour challenging. As a best guess, the current 4% annual increase in production is assumed to continue only until 2034 and is expected to remain stable afterwards. Other feedstock chemicals and by-products related to the controlled HFC production exclusively, such as CFC-114/a, CFC-115 and HCFC-124/a, are projected to decline according to the Kigali Amendment restrictions.

In recent years, the volume of feedstock chemicals used to produce halogenated polymers has been increasing. HCFC-142b is the feedstock chemical in the production of PVDF (polyvinylidene fluoride), which is increasingly used in electrical car batteries. Therefore, an increase of 6% per year is used here until 2034, followed by 4% per year until 2050. For CFC-113/a, the projection is more challenging. First, around a third of the CFC-113/a is used in the production of HFC-134a, which is projected to decline. Second, the demand for CFC-113/a to produce polymers— notably polychlorotrifluoroethylene (PCTFE) from CFC-113—and different specific chemicals is rising. Finally, they can be used to produce HFO-1336mzz, whose future demand is difficult to estimate. Therefore, the increase of 2% per year for CFC-113/a, used for polymers and other chemicals, is only maintained until 2034 and then kept stable.

Based on the above projections, the emissions of all feedstock chemicals and the related atmospheric mixing ratios have been calculated for 2024–2100 (Fig. S4). This forms the basis for deriving the mid-latitude effective equivalent stratospheric chlorine (EESC), a metric that can be used to compare the evolution of ODS relative to their 1980 level, which is regarded as a benchmark for stratospheric ozone recovery. In addition, projected mixing ratios are combined with compound-specific radiative forcings to estimate their effect on Earth's radiative balance and, by extension, their potential influence on climate.

Impacts on stratospheric ozone and climate until 2100

Here, the effect on global emissions and mixing ratios caused by losses from ODS used as feedstock are discussed, using the BAU, LOW and ZERO scenarios. Figure 2 displays estimated emissions from global measurements networks from 2010 to 2023 (see “Methods”), together with projected emissions between 2024 and 2050. The emissions of the LOW and ZERO scenarios are applied in 2024 without any transitional period and therefore instantly diverge from the BAU scenario. For the future emissions, uncertainties are calculated based on a wider range of scenarios, as detailed in Table 1 of the “Methods” section.

Both the BAU and LOW scenarios show a decline in ODS mass emissions (Gg/year) between 2024 and 2050 (Fig. 2A). This decrease occurs because rising emissions from feedstock chemicals are offset by declining emissions from HCFC banks and anticipated reductions from legacy CCl₄ sources. In the LOW scenario, emissions are expected to decline steadily, slightly above the ZERO scenario (without emissions from feedstock production). In contrast, the BAU scenario only shows a decline of around 50%, and emissions are expected to stabilize around 2045. This levelling of emissions is mainly driven by the on-going use of CCl₄ in the production of HFOs and by the expected high consumption of HCFC-22 and HCFC-142b to produce halogenated polymers (Fig. S3). The impact of these sustained elevated emissions on global mixing ratios until 2100 is shown in Fig. S4. Notably, the mixing ratios of CCl₄, HCFC-22, and HCFC-142b, substances with substantial expected feedstock production, are projected to cease declining by 2100.

To assess the effect of ongoing losses from feedstocks and banks on stratospheric ozone, emissions were expressed as CFC-11-equivalents (Fig. 2B). In both the LOW and ZERO scenarios, CFC-11 eq. emissions decline by 2050, from 90 Gg CFC-11 eq. in 2024 to 30 Gg CFC-11 eq. and 15 Gg CFC-11 eq., respectively. In contrast, under the BAU scenario, emissions in 2050 decline only to 63 (55–75) Gg CFC-11 eq. (Fig. 2B).

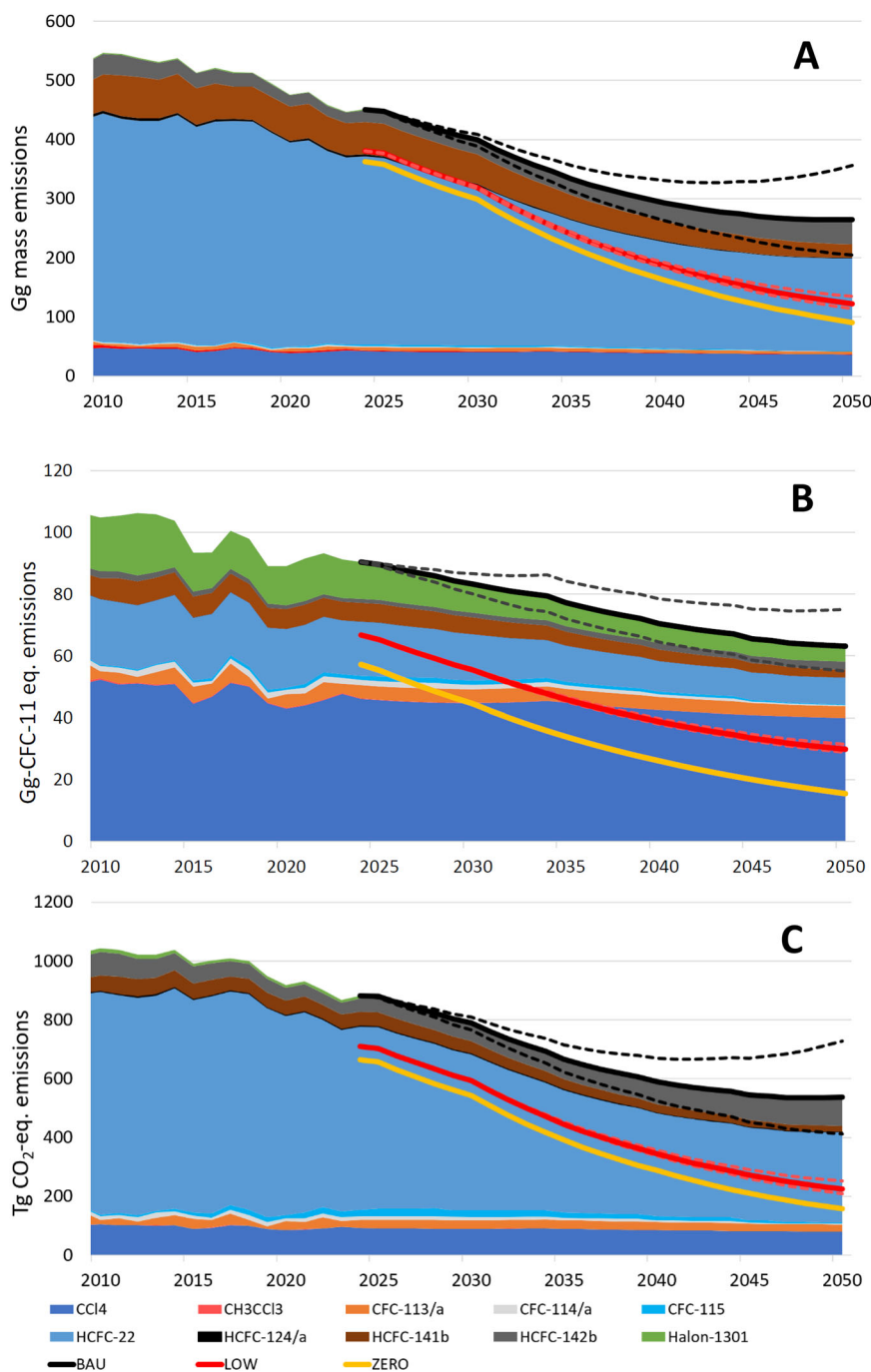


Fig. 2 | Emissions of ODS feedstock chemicals. Historic and future emissions of ODS (ozone-depleting substances) used as feedstocks (2010–2050) in Gg/year (A), Gg-CFC-11 eq./year (B) and in Tg CO₂ eq./year (C). Total emissions arise from feedstock production and usage and other sources, such as losses from banks and other legacy uses. Emissions until 2023 were derived from NOAA (National Oceanic and Atmospheric Administration) and AGAGE (Advanced Global Atmospheric Gases Experiment) measurements (see

“Methods”). Emissions between 2024 and 2050 are shown for the business-as-usual scenario (BAU), with the black line representing total emissions from all sources. The red line shows emissions which would result for the low scenario (LOW), and the yellow line represents the ZERO scenario (projected emissions from banks and other legacies alone, without emissions from feedstock production and usage). Emissions resulting from the uncertainty ranges given in Table 1 are shown as dashed lines.

The gap between the BAU and the LOW scenarios is primarily caused by CCl₄, with additional substantial contributions from Halon-1301, CFC-113/a, HCFC-22, and HCFC-142b (Fig S3). If the emission factor for Halon-1301 were as high as 26%, instead of the assumed 3.6%¹³, it is worth noting that total projected BAU emissions in 2050 would increase by an additional 11 Gg CFC-11-eq.

To evaluate the impact of feedstock-related emissions on stratospheric ozone depletion, their contribution to mid-latitude EESC

was calculated through 2100^{8,16} (see “Methods”). Figure 3A compares the scenarios with 1071 ppt, which corresponds to the mid-latitude EESC level in 1980. This level is widely regarded as a benchmark for the stratospheric ozone recovery. In the ZERO and LOW scenario, the mid-latitude EESC returns to the 1980 value in 2065 and 2066, respectively. In the BAU scenario, this recovery is delayed by about 7 years, i.e. in 2073 (uncertainty range: 2072–2077). The most effective way to reduce this delay would be to

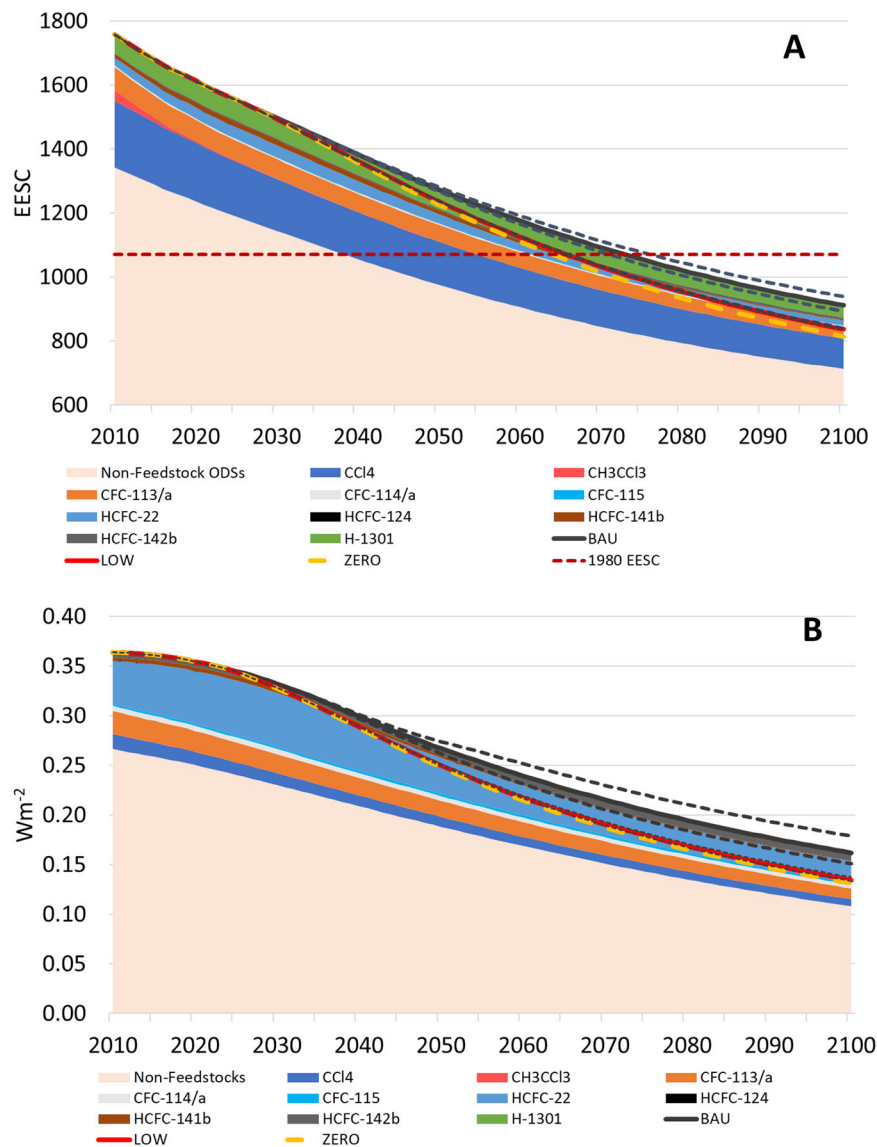


Fig. 3 | Effect of feedstock emissions on stratospheric ozone and climate. A Mid-latitude effective equivalent stratospheric chlorine (EESC) in ppt for individual ODS (ozone-depleting substances) used as feedstocks, including non-feedstock related contributions (e.g. emissions from banks). ODS not largely used as feedstocks (CFC-11, CFC-12, CH₃Cl, CH₃Br and several halons) are grouped as Non-Feedstocks. The black and red lines show the total effect of the business-as-usual (BAU) and the low emission (LOW) scenario, respectively; with uncertainties as dashed black lines.

The ZERO scenario (projected emissions from banks and other legacies alone, without emissions from feedstock production and usage) is shown as a yellow dashed line. Additionally, the mid-latitude EESC value of 1980 is shown as a red dashed line, as a marker for the return date for the mid-latitude stratospheric ozone. **B** Radiative forcing in W m⁻² as a measure for the influence of Non-Feedstocks and individual feedstock ODS emissions on climate within the BAU, LOW, and ZERO scenario. Lines as in (A).

lower feedstock emissions of CCl₄ and to a lesser extent CFC-113/a (Fig. S3), related to their elevated projected emissions compared to other feedstocks, their long atmospheric lifetime, and their strong impact on ozone depletion.

Finally, the projected direct climate impact of feedstock emissions until 2050, expressed in CO₂-equivalents (CO₂-eq., 100-year time horizon), is shown in Fig. 2C. In the LOW scenario, feedstock-related CO₂-eq. emissions gradually decline until 2050, with non-feedstock emissions (ZERO scenario) from banks and other sources still accounting for about two-thirds of the total at that time. In the BAU scenario, emissions are expected to decline until around 2045, after which they stabilize. The forecasted difference of around 300 Tg CO₂-eq. between the LOW and the BAU scenarios in 2050 corresponds to around 0.8% of global anthropogenic CO₂ emissions in 2024¹⁷. The largest contributors to this difference are HCFC-22 and CCl₄, followed by HCFC-142b and CFC-113/a (Fig. S3).

Figure 3B illustrates the contribution of ODS emissions from non-feedstock and feedstock uses to direct radiative forcing until 2100, as a measure of their climate impact. In 2100, the difference in radiative forcing between the BAU and LOW scenarios is 28 (14–45) mW m⁻². The impact of the BAU feedstock consumption scenario compared to the LOW scenario is around 8% of the radiative forcing of all ODS in 2020¹⁰ or 5 times higher than the radiative forcing of the very potent greenhouse gas SF₆ (sulphur hexafluoride) in 2020¹⁰.

In summary, ODS used as feedstocks were excluded from the Montreal Protocol controls at a time when remaining and future emissions from this practice were thought to be too small to substantially affect the timing of the ozone layer recovery. If release rates of ODS from feedstock production were 0.5% or lower, consistent with early industry-based estimates, their current and future influence on stratospheric ozone would be very modest. As a co-benefit, this would

have further strengthened the Montreal Protocol's contribution to reducing associated direct radiative forcing.

However, current emissions are higher than anticipated and may further increase, substantially delaying the recovery of stratospheric ozone. Under the BAU scenario, this delay is projected to be 7 (6–11) years relative to the LOW scenario. The BAU scenario combines the projected increases in feedstock use and production related to current legislation (e.g. Kigali Amendment) with our best estimate of future end-product needs and potential environmental restrictions. For most

feedstock chemicals, their trends in emissions in 2014–2024 were progressed only up to 2034 (i.e. 10 years). For some compounds, however, with higher potential for future growth (e.g. HCFC-22, HCFC-142b), increases were maintained until 2050. If all ODS feedstock production and related emissions will progress up to 2050 at the same rate as in the last decade, this would lead to an average increase in the return date for the stratospheric ozone in mid-latitude which is well above 10 years, instead of the 7 years estimated here. In addition, if the relative emissions of H-1301 feedstock were 26% rather than 3.6% (as

Table 1 | Emissions of ODS (ozone-depleting substances) and their future business-as-usual (BAU) and low (LOW) emission evolution, related to (i) their production and consumption as feedstock chemicals and (ii) other sources, such as emissions from the declining but continuing production for emissive uses of HCFCs, emissions as by-products, emissions from banks, and unexplained emissions for CCl₄

Feedstock emissions relative to produced amounts (BAU/LOW)	Future projections of feedstock production (BAU), uncertainty ranges in brackets	Rationale of current and future projections of changes in ODS emissions.
CCl₄ (4.3% / 0.5%) ODP: 1.1 GWP-100: 2200	2025–2034: +4% /yr (+2 – +6%) 2035–2100: no increase/decrease	a) Feedstock usage: Expected growth in HFOs will drive increasing demand for CCl ₄ as feedstock, uncertain development of HFO growth in the distant future Expected decline in production of perchloroethene, used as a feedstock of HCFCs b) By-product of 1,2-dichloroethane production will grow with VCM/PVC demand 5 Gg in 2022, increasing by 2%/yr to 2050. c) Legacy and unexplained emissions: 21 Gg/yr in 2022, decreasing by 5%/yr to 2050 (Fig S5)
CFC-113/113a (3.6% / 0.5%) ODP: 0.8 (all CFC-113) GWP-100: 5525 (50% CFC-113/50% CFC-113a)	For all uses, except for HFC-134a production 2025–2034: 2% /yr (0% – +4%) 2035–2100: no increase/decrease For use for HFC-134a: Decrease relative to HFC-134a production [§]	a) Feedstock usage: Small growth of CFC-113 for CTFE polymer production; uncertain growth of CFC-113a in HFO-1336mzz production Plateau and decline in amount used for HFC-134a [§] b) By-product emissions: negligible c) Bank emissions: negligible
CFC-114/114a (3.6% / 0.5%) ODP: 1 GWP-100: 7420 (all CFC-114a)	Decrease relative to HFC-134a production [§]	a) Feedstock usage: Plateau and decline in amount used for HFC-134a [§] b) By-product: potentially small contribution from HFC-125 production: not included c) Bank emissions: negligible
CFC-115 (0.8% / 0.4%) as by-product only ODP: 0.6 GWP-100: 9600	Decrease relative to HFC-125 production [†]	a) Feedstock usage: not used b) By-product: 0.8% of HFC-125 production ^{† 25} Plateau and decline c) Bank emissions: negligible
CH₂CCl₃ (3.6% / 0.5%) ODP: 0.1 GWP ¹⁰⁰ : 161	2025–2050: –6% /yr (–8% to –4%) 2050–2100: no increase/decrease	a) Feedstock usage: Declined between 2014 and 2024. Expected to decline further due to relatively high cost of this production route to HCFC-142b vs. VDC (Fig. 1), and route possibly forms some unwanted HFC-143a by-product b) By-product: no emissions c) Bank emissions: negligible
HCFC-22 (3.6% / 0.5%) ODP: 0.055 GWP-100: 1960	2025–2050: +4% /yr (+2% – +6%) 2050–2100: no increase/decrease	a) Feedstock usage: Fluoropolymer-related growth (e.g. PTFE, FEP) b) By-product: no emissions c) Bank emissions: – 6.5%/yr from 2025–2050 d) Emissive uses: Decreasing to –0 between 2025–2040 [†]
HCFC-141b (3.6% / 0.5%) ODP: 0.11 GWP-100: 860	2025–2050: –2% /yr (–4% – 0%) 2050–2100: no increase/decrease	a) Feedstock usage: Declined between 2014 and 2024 b) By-product: no emissions c) Bank emissions: Emissions from banks decreasing from 2025–2050 [§] d) Emissive uses: Decreasing to –0 between 2025–2040 [†]
HCFC-142b (3.6% / 0.5%) ODP: 0.065 GWP-100: 2300	2025–2034: +6% /yr (+4% – +8%) 2035–2050: +4% /yr (+2% – +6%) 2050–2100: no increase/decrease	a) Feedstock usage: Growth in PVDF polymer production b) By-product: no emissions c) Bank emissions: Emissions from banks decreasing from 2025–2050 [§] d) Emissive uses: Decreasing to –0 between 2025–2040 [†]
HCFC-124/a (3.6% / 0.5%) ODP: 0.022 GWP-100: 597	Decrease relative to the combined HFC-125 and HFC-134a production [†]	a) Feedstock usage: Plateau and decline in amount used as an intermediate for HFC-125 and HFC-134a [†] b) By-product: no emissions c) Bank emissions: Expected to decline by –5%/yr between 2025 and 2050 d) Emissive uses: none
Halon-1301 (3.6% / 0.5%) ODP: 10 GWP-100: 7200	2025 – 50: +4% /yr (+2% – +6%) 2050–2100: no increase/decrease	a) Feedstock usage: Growth in use for pharmaceuticals and insecticides b) By-product: no emissions c) Bank emissions: decreasing by 5%/yr from 2025–2050

§ It is assumed that in 2023 around 30% of the CFC-113 production was converted to CFC-113a and from there to CFC-114/a, which was then used to produce HFC-134a. For the projection of the future use of CFC-113/a and CFC-114/a for this purpose, the Kigali Amendment scenario (KA-2022) of Velders et al.²⁵ was used.

† For the historic and future projections of HFC-125, production data from Velders et al.²⁵ were used.

* For the HCFC-124/a usage and production the average of the HFC-125 and HFC-134a production from Velders et al.²⁵ were used.

† The production of HCFCs for emissive uses (e.g. air conditioner fluids, foam blowing agent) will be phased out globally by 2040 according to the Montreal Protocol.

The Ozone-Depletion Potentials (ODP) are shown as defined in the Montreal Protocol and the Global Warming Potentials (GWP-100) are from AR6 of the Intergovernmental Panel on Climate Change (IPCC)²⁶.

suggested¹³), the return of the mid-latitude EESC to 1980 levels would be further delayed by an additional 4 years.

Methods

Derived historic measurement-based emissions until 2023

For the calculation of global measurement-based emissions, data from AGAGE (Advanced Global Atmospheric Gases Experiment) and NOAA (National Oceanic and Atmospheric Administration, USA) were used^{7,18,19}, applying a global 12-box model²⁰. Briefly, the transport and process model is a zonally averaged model of the atmosphere, divided at the equator and 30°N and 30°S, and the surface, 500 hPa and 200 hPa. Loss process uses a first order offline chemistry scheme. Emissions estimates use monthly mean measurements of background air from seven sites in the AGAGE network, which are representative of the meridional semi-hemispheres. For the NOAA network, globally averaged annual mole fractions represent weighted annual averages from measured monthly mole fractions made at remote locations. Data from these measurement sites were used Alert, Nunavut, Canada, 82.5° N 62.5° W (NOAA); Zeppelin Mountain, Svalbard, 78.9° N, 11.9° E (AGAGE); Summit, Greenland, 72.6° N 38.4° W (NOAA); Barrow, Alaska, USA, 71.3° N 156.6° W (NOAA); Mace Head, Ireland, 53.3° N 9.9° W (AGAGE, NOAA); Jungfraujoch, Switzerland, 46.6° N, 8.0° E (AGAGE); Niwot Ridge, Colorado, USA, 40.1° N 105.6° W (NOAA); Trinidad Head, California, USA, 41.0° N 124.1° W (AGAGE, NOAA); Mauna Loa, Hawaii, USA, 19.5° N 155.6° W (NOAA); Cape Kumukahi, Hawaii, USA, 19.6° N 154.9° W (NOAA); Ragged Point, Barbados, 13.2° N, 59.4° W (AGAGE); Cape Matatula, American Samoa, 14.2° S 170.6° W (AGAGE, NOAA); Kennaook / Cape Grim, Tasmania, Australia, 40.7° S 144.7° E (AGAGE, NOAA); Palmer Station, Antarctica, 64.8° S 64.1° W (NOAA); and South Pole, Antarctica, 90.0° S (NOAA).

Emissions are estimated using Bayesian inference, which includes errors and uncertainties due to transport, measurements and atmospheric lifetimes.

Calculation of the mid-latitude EESC

For each compound and for each scenario described in this paper, future surface mixing ratios are calculated from emissions from the BAU, LOW, and ZERO scenarios together with atmospheric lifetimes²¹ using a global box model²². These mixing ratios are then used to calculate the future EESC representative of mid-latitude ozone loss, using the formalism developed in Engel et al.²³. Furthermore, mixing ratios are used to estimate the radiative forcing by multiplying the mixing ratios by the radiative efficiencies²¹.

Projected feedstock production and consumption between 2025 and 2100 for the BAU and LOW emission scenarios

The relative feedstock emissions from the business-as-usual (BAU) and the low (LOW) emission scenarios are explained in this section and summarized in Table 1. The projected increase in the use of individual ODS feedstocks between 2025 and 2034 is related to their trends in the production and consumption between 2014 and 2024 (Fig. S1), taking into consideration some additional information, explained in Table 1. For CCl₄, an annual growth rate of 4% (2–6%) was used from 2025 to 2034, based on the expected high growth in the production of HFOs, as the main fluorinated replacement for the restricted HFCs. Due to the uncertainty connected with the future production of HFOs and the usage of CCl₄ as a feedstock for phased-down HFCs, production was then assumed to be stable afterwards. For HCFC-142b, an annual growth of 6% (4–8%) is justified by its main usage as a feedstock for polyvinylidene fluoride (PVDF), which is used in advanced electric car batteries (see below). Between 2035 and 2050, a smaller annual increase of 4% (2–6%), representing the longer-term growth perspective, was used. For others, such as 1,1,1-trichloroethane and HCFC-141b, the production and consumption as feedstock have declined in recent years (Fig. S2, Table 1), which is projected forward on an individual basis.

The most important categories of current emissions are summarized in Table 1 (as shown in Fig. 1), separated into (a) feedstock emissions, (b) by-product emissions, (c) bank, legacy and unexplained emissions, and (d) emissions from emissive uses (only for HCFCs).

Data availability

The datasets generated during and/or analysed during the current study are available at: <https://doi.org/10.5281/zenodo.18233223>²⁴

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Author contributions

S.R., D.S., J.S.D. and S.S. designed the study. S.R., D.S., L.M.W., M.J.L., S.A.M., M.R., L.J.M.K. and J.S.D. provided and analysed the data and contributed to the discussions on projections. D.S. and L.J.M.K. provided information on technical details on the use of feedstocks. G.J.M.V. provided HFC projections and support of the scenarios. D.S. and Q.L.

provided knowledge on the use of CCl₄ and supported the scenarios. S.S., M.K.V., S.P. and L.E. provided guidance on the paper structure and review. S.R. wrote the paper with contributions from all the co-authors.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Stefan Reimann.

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