

Technical note: A method for calculating offsets to ozone depletion and climate impacts of ozone-depleting substances

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Abstract. By phasing out production and consumption of most ozone depleting substances (ODSs), the Montreal Protocol on
10 Substances that Deplete the Ozone Layer (Montreal Protocol) has avoided consequences of increased ultraviolet (UV)
radiation, and will restore stratospheric ozone to pre-1980 conditions by mid-century, assuming compliance with the phaseout.
However, several studies have documented an unexpected increase in emissions and suggested unreported production of
trichlorofluoromethane (CFC-11) and potentially other ODSs ~~that occurred~~ after 2012 despite production phaseouts under the
Montreal Protocol. Furthermore, because most ODSs are powerful greenhouse gases (GHGs) there are significant climate
15 protection benefits in collecting and destroying the substantial quantities of historically allowed production of chemicals under
the Montreal Protocol that are contained in existing equipment and products and referred to as ODS “banks”. This technical
note presents a framework for considering offsets to ozone depletion, climate forcing, and other environmental impacts arising
from occurrences of unexpected emissions and unreported production of Montreal Protocol controlled substances, as recently
experienced and likely to be experienced again. We also show how this methodology could be applied to the destruction of
20 “banks” of controlled ODSs and GHGs, or to halon or other production allowed under a Montreal Protocol Essential Use
Exemption or Emergency/Critical Use Exemption. Further, roughly estimate the magnitude of offset each type of action could
provide for ozone depletion, climate, and other environmental impacts should Montreal Protocol Parties agree require remedial
action.

1 The stratospheric ozone layer and the Montreal Protocol

25 The stratospheric ozone layer shields Earth against ultraviolet (UV) radiation that causes skin cancer and cataracts, suppresses
the human immune system, and damages agricultural and natural ecosystems including terrestrial carbon sinks; and deteriorates
the built environment (United Nations Environment Programme (UNEP) Environmental Effects Assessment Panel (EEAP),
2018; Bais et al., 2018; Young et al., 2021). Ozone-depleting substances (ODSs) deplete stratospheric ozone, thus increasing
the amount of UV radiation reaching Earth’s surface. Some ODSs, primarily chlorofluorocarbons (CFCs),
30 hydrochlorofluorocarbons (HCFCs), carbon tetrachloride (CTC or CCl₄), and halons; are also potent greenhouse gases (GHGs)

(Ramanathan, 1975) (World Meteorological Organization (WMO), 2022), as are ~~the long-lived ODS-substitutes that are hydrofluorocarbons (HFCs)~~ used as ODS-substitutes.

35 The 1987 Montreal Protocol is an international treaty that has already phased out more than 99% of the production and consumption of about 100 ozone-depleting GHGs and will soon phase down about a dozen ~~hydrofluorocarbon (HFC) GHGs~~ HFCs that don't contain ozone-depleting chlorine or bromine. The United States Environmental Protection Agency (US EPA), has estimated that ODS phaseout under the fully revised and Amended Montreal Protocol compared with a scenario of no controls will prevent approximately 443 million cases of skin cancer, 2.3 million skin cancer deaths, and 63 million cataract cases for people in the United States born in the years 1890–2100 (EPA, 2020; Madronich et al., 2021). Global impacts are significantly higher considering that these estimates are for the US alone, representing about 4.25% of global population, and do not include the economic consequences of the full spectrum in health, agricultural productivity, and product deterioration. Even a seemingly small increase in UV radiation from unexpected emissions of unreported CFC-11 production has been estimated to contribute to an additional 31,600 to 59,800 cases of skin cancer and 170 to 340 deaths and 4,100 to 9,300 cases of cataracts that would otherwise have been avoided in the US alone (EPA, 2020). Consider also that every ecosystem would suffer adverse effects owing to any increase in damaging UV radiation (Young et al., 2021). Furthermore, the family and community consequences are far worse in societies without adequate health and where food is already in short supply (Andersen and Sarma, 2002).

In May 2018, scientists warned that emissions of CFC-11 had unexpectedly increased despite a production phaseout under the Montreal Protocol (Montzka et al., 2018). In May 2019, scientists pinpointed $\sim 60 \pm 40\%$ of unexpected emission increase to an area in China's north-eastern provinces of Shandong and Hebei and found no evidence of a significant increase in CFC-11 emissions from any other locations where monitoring stations are sensitive to emissions on a regional scale (Rigby et al., 2019; Adcock et al., 2020). Over the course of 2018 and 2019, the unexpected emissions and unreported production of CFC-11 globally and from eastern China dropped substantially (Montzka et al., 2021; Park et al., 2021). Enhanced emissions of dichlorodifluoromethane (CFC-12) from eastern China, perhaps associated with CFC-11 production, have also been suggested (Park et al., 2021). A separate study, which analyzed 27 whole air samples collected in 2016 over Hebei province, implied new production and emissions of CFC-11, CFC-12, and 1,2-dichlorotetrafluoroethane (CFC-114) in various locations in China during spring 2016 (Benish et al., 2021). Another analysis of global atmospheric concentrations of CFC-11, CFC-12, and 1,1,2-trichloro-1,2,2-trifluoroethane (CFC-113) confirmed unexpected emissions of CFC-11, but suggested the possibility of unexpected emissions of these other gases during 2014–16 and called for further investigation of potential sources of these emissions (Lickley et al., 2021). Increases in global emission and atmospheric concentrations of several CFCs with production allowed under the Montreal Protocol for use as feedstocks in the production of hydrofluorocarbons, e.g., 1,1,1-Trichloro-2,2,2-trifluoroethane (CFC-113a₇), CFC-114a and chloropentafluoroethane (CFC-115₇), are also being observed, together with

emission increases in CFC-13 and CFC-112a, although the driver of the increase for these latter two CFCs is unclear (Western
65 et al., 2023).

Emissions of another Montreal Protocol-controlled substance, ~~carbon tetrachloride (CCl₄), CTC~~, also have been substantially
higher than expected after the phaseout of CFC production (SPARC, 2016). ~~CTC₄~~ is used as a feedstock in the production of
CFC-11 and CFC-12 and as a solvent. While the ongoing ~~CTC₄~~ emissions have not yet been implicated in non-compliance
70 with the Montreal Protocol, they add significantly to the ozone-depleting halogen burden of the atmosphere. Hence,
stakeholders may benefit from understanding how to offset the impacts of such emissions on stratospheric ozone and its
recovery and to offset the impacts on climate forcing.

Here we propose an approach for calculating the quantity of ODSs for offsetting adverse environmental impacts arising from
75 occurrences of unreported and unauthorized production ODSs and chemical substitutes such as HFCs. These offsets could take
the form of preventing the emissions of ODSs and HFCs that were legally produced and would otherwise be emitted, such as
through ~~the~~ collecting and destroying banks of these chemicals. Other options are highlighted that could also be considered to
offset the ozone depletion, climate, and other environmental impacts arising from instances of unexpected emissions or
unreported production should Montreal Protocol Parties agree require remedial action. Note that an offset approach could also
80 be applied to management and destruction of ODS banks or could be used to manage halon production allowed under a
Montreal Protocol Essential Use Exemption in cases where entities are allowed to use and emit available halon banks.

An important aspect of offsetting impacts relates to the timing of the impact compared to the offset. Given the added
uncertainties associated with estimating the year-to-year impacts of unexpected or illicit production and associated emission
85 that one might hope to offset, we focus here on offsetting cumulative impacts. We note that this approach is the only possible
path to offset adverse impacts of uncertain emissions that occurred in the past. We also recognize that the approach of offsetting
impacts with a cumulative timeframe and not year-by-year will lead to a different time-history for an impact compared to the
offset, especially when the chemical being considered for supplying an offset has a substantially different lifetime than the
chemical causing the adverse impact. This latter point will likely always be true when devising an offset to an impact that has
90 already occurred. Consider however, that environmental justice usually requires judgement of both the environmental impact
and which victims are worthy and qualified for compensation. The approach to calculating offsets presented here ~~puts the
atmosphere back where it would have been without unauthorized ODS and HFC production and emissions~~ offsets cumulative
impacts but does not compensate those harmed by increased UV radiation.

2 Usage implications on estimating the magnitude of impacts to be offset

95 Atmospheric observations of a long-lived ODS and HFC substances can provide an estimate of an unexpected emission magnitude that is to be offset. For many halocarbon substances, however, anomalous emissions will represent only a fraction of the total amount of chemical produced and the total cumulative impact, owing to the retention of chemical in cooling appliances, fire protection equipment, closed-cell foams, etc., ~~as so-called~~ “and emission from the banks” until emitted long well after original production and use. Relating changes in atmospheric concentrations to production and, therefore, a more
100 complete picture of the cumulative impact into the future as the banked chemical slowly escapes to the atmosphere, requires an understanding of how substances are produced and used. We summarize in the Supplemental Information typical historical production and uses for several ODSs for which unexpected emissions have been observed.

3 Quantifying ozone depletion, environmental, and climate impacts

The damages from unexpected emissions and unreported production of substances controlled under the Montreal Protocol can
105 be quantified for the impacts related to ozone depletion for ODSs, UV radiation exposure to estimate health and environmental effects, damage to the terrestrial carbon sink, deterioration of the build environment, and climate forcing for GHGs. In an ideal scenario, an offset would match the impacts year-by-year. However, this is likely to be impractical due to differences in the time-dependent impacts of different chemicals due to differences in potency and lifetimes and that unreported production and emissions of the controlled substances to be offset will likely precede any offset actions. For these reasons, we focus here
110 on estimating cumulative impacts and offsets, although we realize that there are limitations of this approach, for example in cases where the impact is non-linearly related to the atmospheric abundance, as in the case of biological effects that depend on behavioral and other factors (Slaper et al., 1996). Specifically, we propose to use the established metrics of ozone depletion potential (ODP) and global warming potential (GWP) when calculating offsets associated with an emission. While the ODP is
115 “defined as the ratio at steady-state of calculated ozone column change for each mass unit of a gas emitted into the atmosphere relative to the calculated depletion for the reference gas CFC-11 (Fisher et al., 1990)²”, it is also true that the ODP can be reliably used to estimate the cumulative impacts arising from a pulsed emission (Prather, 2002). In this way, ODP integrates the cumulative impact on the ozone column of a chemical relative to CFC-11 over the lifetime of the chemical and the timescale of secondary impacts. The ODP differs from the GWP in one important respect, however, in that the GWP reflects the ratio of a change in radiative forcing from an emission of gas relative to that same mass emission of carbon dioxide *integrated over a*
120 *specific time horizon* (usually 100 or 20 years), and not over the lifetime of the chemical and its impacts. Choosing an appropriate integration period for estimating the impact and deriving an appropriate offset therefore will require a choice to be made, and this choice hinges on the relative importance of near-term vs long-term impacts. We discuss additional considerations of impacts and offset metrics in this section by type of impact and conclude with an illustrative example.

3.1 Ozone depletion for ODSs

125 The approach of offsetting, through a reduction in emission or production of an ODS, the cumulative ozone depletion arising
from unexpected or illicit emissions after weighting those emissions by the ODP_i is supported by the near-linear relationships
between cumulative emissions of a particular long-lived ODS and stratospheric ozone impacts from that ODS, both globally
and over the Antarctic (Keeble et al., 2020; Fleming et al., 2020; Dhomse et al., 2019) as summarized in (WMO, 2021). This
is because the impacts on stratospheric ozone of an emission roughly scale by the amount of chlorine (Cl) released in the
130 stratosphere, all other factors (aerosol loading, etc.) being equal, so can be applied to CFC-12, CTC, and other ODS species
(Dhomse et al., 2019; Keeble et al., 2020; WMO, 2021). Other metrics such as the Integrated Ozone Depletion (IOD) could
be used for quantifying the impact on stratospheric ozone of an emission to be offset, and use of this metric would provide
results very similar to use of ODP unless the chemical being used to offset an impact had a substantially different loss frequency
in the troposphere and stratosphere (Pyle et al., 2022).

135 The ODPs used in Table 1 are based on atmospheric model simulations and can be expressed as a semi-empirical relationship:

$$ODP_i = \frac{n_{Cl}}{3} \times \frac{f_i}{f_{CFC-11}} + \frac{\tau_i}{\tau_{CFC-11}} + \frac{m_{CFC-11}}{m_i} \quad (1)$$

where n_{Cl} is the number of chlorine atoms in the molecule, f_i is the fractional release factor for the molecule, τ_i is the total
lifetime, and m_i is the molecular mass of the molecule (Burkholder et al., 2022).

The IOD for comparison, and not used here, is given by Eq. (2):

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$$IOD = K E_{Eq} \left(\frac{\tau_{atmos}}{\tau_{strat}} \right) \quad (2)$$

where $K=100 \pm 16$ Dobson Units years per Tg Cl, E_{Eq} is the total emission in Tg Cl, multiplied by the ratio of the whole
atmosphere lifetime of the molecule to its stratospheric lifetime, $\tau_{atmos}/\tau_{strat}$ (Pyle et al., 2022).

3.2 Environmental impacts from ozone depletion

UV radiation exposure can be estimated from ozone depletion to estimate health and environmental effects. For example, the
145 EPA used its Atmospheric and Health Effects Framework (AHEF) model to estimate that in the U.S.-US alone the unexpected
CFC-11 emissions,¹ absent offset, would result in nearly 60,000 cancer deaths through 2100 that compliance with the Montreal
Protocol would have avoided (EPA, 2020). This and other health effects models can be extrapolated taking into account
geographic location, genetic vulnerability, lifestyle differences, and access to preventative and therapeutic mitigation (Slaper

¹ This estimate is based on the “bank scenario”, which assumes that CFC-11 emissions began increasing in 2012 above those expected under the reference WMO A1 scenario, peak around 77 Gg/yr in 2015–2017, then decline sharply through 2100. While the end date of unreported production is unclear, the report states that: “In the fourth scenario, CFC-11 emissions were estimated based on Dhomse et al. (2019), which constructs an emissions scenario curve based on initial rapid increase in CFC-11 emissions and slower release from accumulated CFC-11 banks. This scenario first takes the estimate of 13 Gg/year in new emissions due to unreported production and assumes an immediate production release rate of 15 percent followed by 3.5 percent/year. This creates a gradually decreasing emissions curve where CFC-11 emissions continue past 2100 due to releases from the accumulated bank even after production goes to zero²²²” (EPA, 2020).

et al., 1996; Longstreth et al., 1998; Struijs et al., 2010; van Dijk et al., 2013). A calculation of the health and environmental impacts from ozone depletion and global warming of emissions is beyond the scope of this paper, as the authors are unaware of simplified metrics for these impacts analogous to the metrics for estimating ozone column ~~and climate impacts and global warming potential~~. In addition to human health impacts, UV exposure can harm aboveground plant biomass and diminish the uptake of carbon dioxide (CO₂) by the terrestrial biosphere in its capacity as a carbon sink. Studies suggest a UV response strength of a 3% reduction in biomass for a 10% increase in plant-weighted surface UV fluxes which can be related to total column ozone (Young et al., 2021). These impacts could also be included in deriving appropriate offsets if desired in terms of ozone offsets for UV impacts and protection of carbon sinks or GHG mitigation to offset the CO₂ impacts (section 3.3).

3.3 Climate forcing for greenhouse gases (GHGs)

Offsets in carbon emissions are measured in tonnes of carbon dioxide-equivalent (CO₂-eq) using ~~Global Warming Potentials (GWP)~~GWPs from the most recently published set, e.g. (Burkholder et al., 2022). The issue of timescales is also important with this metric, as the GWP involves a comparison of the cumulative climate impact over a specified time interval of a pulse emission for chemicals having different lifetimes. While 100-year GWP are most commonly used to capture the longer-term warming effects of long-lived greenhouse gases like CO₂ and CFCs, the use of 20-year GWP may be more relevant when considering near-term warming impacts of potent but short-lived GHGs like most HFCs, such as 1,1,1,2-Tetrafluoroethane (HFC-134a) (13.5 year lifetime), difluoromethane (HFC-32) (5.27 year lifetime), Pentafluoroethane (HFC-125) (30.7 year lifetime) (Burkholder et al., 2022). Such near-term impacts are particularly relevant to temperature goals such as limiting warming to 1.5°C with no- or limited overshoot, noting that the possibility of crossing the 1.5°C warming target of the Paris Agreement as soon as the 2030s (Abernethy and Jackson, 2022; Xu et al., 2018; Intergovernmental Panel on Climate Change, 2021).

The GWP for a molecule x is given by Eq. (3):

$$GWP_x = \frac{\int_0^{t'} a_x \exp\left(-\frac{t}{\tau_x}\right) dt}{\int_0^{t'} a_{CO_2} R(t) dt} \quad (3)$$

where a is the radiative efficiency per unit mass, τ_x is the global lifetime of molecule x , $R(t)$ is the decay time of a pulse of the reference gas CO₂ and t' is the time horizon over which the integrated radiative forcing is calculated (Daniel et al., 2012).

3.4 Illustrative offset calculation

When deriving offsets based on anomalies in emissions, it is important to remember to consider the potential for future emissions that have not yet escaped to the atmosphere (e.g., from banked chemicals that were produced illicitly but that have not yet reached the atmosphere, see earlier text). In the case of the unexpected CFC-11 emissions, the TEAP Task Force found: “the estimated cumulative total of unreported CFC-11 production is 320-700 kilotonnes in the period 2007-2019. Assuming usage in closed-cell foam production, this cumulative unreported CFC-11 production would lead to an estimated increase in the magnitude of the CFC-11 bank of 300 (266-333) kilotonnes by the end of 2019.” (TEAP, 2022) Taking the cumulative

180 total of unreported production of 320-700 kilotonnes CFC-11, we calculate an ODP-weighted emission of 320–700 kilotonnes and GWP₂₀ of 2.7–6.0 GtCO₂e and GWP₁₀₀ of 2.1–4.5 GtCO₂e (Table 1). To calculate equivalent offsets, the formula [below in Eq. \(4\)](#) is considered below to derive offsets for three [potential substances ODS](#) that are being phased out under the Montreal Protocol [with the largest remaining eligible production and consumption](#) (Table 1).

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$$\text{Mass of Chemical X (kilotonnes)} = [\text{Mass CFC-11 (kilotonnes)}] \times [\text{metric for CFC-11}] / [\text{metric for Chemical X}] \quad (4)$$

Offsetting this cumulative total CFC-11 production on ozone depletion would require preventing emission of 8,420 to 10,840 kilotonnes of HCFC-22, either through the destruction of that amount from existing banks or as reduced production allowances. In this case, the amount of HCFC required to offset the cumulative ozone impacts is greater than the amount that would be needed to offset the global warming impacts under both 20- and 100-year time horizons. For comparison, the estimated cumulative HCFC-22 production allowed under the Montreal Protocol phaseout schedule for controlled uses (excluding feedstocks) through 2040 to be on the order of 1,300 kilotonnes (Table 2). Even if recent HCFC-22 production from 2021-2023 were considered available for recovery and destruction, this would only amount to about 900 kilotonnes available for offset. Due to the low ozone depleting potential of HCFC-22, it would take the additional step of recovery and destruction of CFC banks or some other actions to offset the ozone impacts of the unexpected CFC-11 production. [Elimination or prevention of remaining eligible consumption for 1,1-Dichloro-1-fluoroethane \(HCFC-141b\) and 1-Chloro-1,1-difluoroethane \(HCFC-142b\) would also be insufficient, as those magnitudes are estimated to be 1.3 kt and 7.6 kt, respectively, based on reporting through the 92nd meeting of the Executive Committee of the Multilateral Fund, as reported in Table 4-1 of the TEAP Replenishment Task Force Supplementary Report \(TEAP, 2023b\). However, narrowing exemptions for production of ODS for feedstock uses could expand the amount of ODS available for offset \(see Table 2\).](#)

Table 1. CFC-11 cumulative production in ODP- and GWP-weighted and calculated mass of HCFC-22, HCFC-141b, and HCFC-142b to achieve equivalent ODP or GWP-offsets. ODP and GWP values are from Table A-5 in the 2022 Quadrennial Ozone Assessment (Burkholder et al., 2022).

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	ODP Weighted (kilotonnes)	GWP ₂₀ Weighted (GtCO ₂ e)	GWP ₁₀₀ Weighted (GtCO ₂ e)
CFC-11			
Conversion values for 1 kilotonne of CFC-11	1	8560	6410
Estimated cumulative total of unreported CFC-11 production in the period 2007-2019	320–700	2.7–6.0	2.1–4.5
HCFC-22			

Conversion values for 1 kilotonne of HCFC-22	0.038	5610	1910
Kilotonnes of HCFC-22 that would need to be destroyed to offset unreported CFC-11 production in terms of ODP or GWP equivalent impact	8,420–10,840	488–1,070	1,070–2,350
HCFC-141b			
Conversion values for 1 kilotonne of HCFC-141b	0.102	2590	808
Kilotonnes of HCFC-141b that would need to be destroyed to offset unreported CFC-11 production in terms of ODP or GWP equivalent impact	3,140–6,860	1,060–2,310	2,540–5,550
HCFC-142b			
Conversion values for 1 kilotonne of HCFC-142b	0.057	5400	2190
Kilotonnes of HCFC-142b that would need to be destroyed to offset unreported CFC-11 production in terms of ODP or GWP equivalent impact	5,610–12,300	510–1,110	937–2,050

~~Table 1. CFC-11 cumulative production in ODP and GWP and calculated mass of HCFC-22, HCFC-141b, and HCFC-142b to achieve equivalent ODP or GWP offsets. ODP and GWP values are from Table A-5 in the 2022 Quadrennial Ozone Assessment.~~

4 Offsets are one option to maintain the integrity of ozone and climate protection under the Montreal Protocol

210 While any given instance of unexpected and unreported emissions may seem small in terms of atmospheric impacts, such impacts are cumulative and in absolute terms significant compared to other environmental violations where compensation is sought—consider for example the settlement ~~between the US government and requiring~~ Volkswagen (VW) ~~requiring VW~~ to provide nearly US\$3 billion to an Environmental Mitigation Trust to “fully remediate the excess NO_x emissions from the illegal vehicles” (Breyer, 2016). Stratospheric ozone depletion and climate-forcing offsets can compensate for unexpected and

215 unreported production by: reducing production or emissions of an ODS produced legally prior to phaseout under the Montreal Protocol or by preventing emissions or production of an ODS not yet subject to the Montreal Protocol’s phaseout requirements (e.g., ~~trifluoromethyl iodide (CF₃I-), methylene chloride (CH₂Cl₂-), or nitrous oxide (N₂O-))~~); and/or with respect to climate forcing, avoiding cumulative emissions or removing GHGs equivalent to the near term (20-year GWP) forcing of the unexpected and unreported emission to help prevent triggering tipping points and longer-term climate change (Lenton et al.,

220 2019). In the absence of chemical offsets being applied, an alternative approach might be to calculate cumulative health impacts and determine monetary compensation and/or punitive damages of loss in health, life, productivity, ecological impact, and materials degradation.

Offsets in ozone depletion are measured in tonnes of CFC-11 emission-equivalent (as an ODP-weighted emission). In the case of ozone depletion, the size of the offset estimated to be needed would ensure that the cumulative adverse impact of the unreported or illicit activity would be offset. Such an approach would contribute to ozone recovery and towards offsetting the health and environmental damage done prior to mitigation.

5 Potential actions that could offset the ozone depletion and climate impacts of unexpected and unreported production

In Table 2 we present a non-exhaustive list of potential actions that could be used to offset the ozone depletion, climate, and other environmental impacts arising from instances of unexpected and unreported production that Parties may agree warrant remedial action. Any of these measures could also be employed to offset the ozone and climate impacts of Essential Use Exemptions (EUEs) for ODSs other than HCFCs, and [methyl bromide \(including emergency EUEs\)](#), Critical Use Exemptions (CUEs) for methyl bromide, ~~or emergency use~~, [\(including emergency CUEs\) \(UNEP, Ozone Secretariat Decisions IV/25, IX/6, IX/7, and TEAP Handbook 2005\).](#)² We provide indicative numbers on the potential available offsets for each type of action.

Table 2. Overview of potential offset activities and indicative available offsets.

Potential Offset Activity	Indicative Available Offsets for Potential Activity
Accelerate the HCFC phaseout faster than mandated by the Protocol (reducing both ozone depletion and climate forcing)	Based on baseline levels, phaseout schedule and current production in 2021 from Table 2 in Multilateral Fund (MLF) document 92/5 (MLF, 2023), we estimate the cumulative allowed HCFC production for controlled uses (excluding feedstocks) from 2024 through phaseout in 2040 to be on the order of 50,000 ODP tonnes, primarily HCFC-22, which is equivalent to approximately 1,300 kilotonnes of HCFC-22. Allowed production for controlled uses from 2021 to 2023 totaled about 900 kilotonnes of HCFC-22.
Limiting emissions associated with feedstock exemptions	While HCFC-22 production for controlled uses is phasing out, production for exempted feedstock uses is increasing as a share of total production. HCFC-22 production for feedstock uses was 56% of total reported production in 2017 (UNEP and TEAP, 2019) compared with reported

² [Numerous decisions of the Parties to the Montreal Protocol establish and interpret criteria and procedures for EUEs and CUEs, and related emergency exemption applications. Examples of key decisions concerning EUEs and CUEs are provided in the references.](#)

	<p>production for controlled uses (MLF 2023). If feedstock production exemptions were to be revisited by the parties to the Montreal Protocol (Andersen et al., 2021), then this sector could be considered in an offset framework.</p> <p>Total annual feedstock production in 2019 was estimated at 558 ODP-weighted kilotonnes, with emissions of 15.0–18.7 ODP kilotonnes (Daniel et al., 2022).</p>
Leapfrog HFCs to low-GWP energy-efficient, next-generation fluids or technology (also mitigating ozone and climate forcing)	<p>Estimated baseline annual HFC consumption for Article 5 parties for 2020–2022 was estimated to total 1.1 billion tonnes CO₂e using Annex F GWP₁₀₀ in Table 3-2 (UNEP and TEAP, 2023). Non-A5 parties are currently subject to a 10% reduction compared to baseline consumption levels, and in 2024 will start the 40% reduction step. For a sense of scale of potential for acceleration of phasedown, the baseline HFC consumption for the United States is 300 million metric tonnes (U.S. Environmental Protection Agency, 2023) and the European Union is 164 million metric tonnes (UNEP, 2023) (both use 2007 IPCC GWP₁₀₀ values).</p>
Accelerate the HFC phasedown and transition to technologies with lower environmental impacts including non-fluorocarbon replacements (also not-in-kind -- NIK)	
Collect and destroy ODSs and HFCs banks (ozone and climate mitigation for ODS destruction; climate mitigation only for HFC destruction)	<p>CFC-11 banks have been estimated to range from 70 to 1 475 kilotonnes for 2018, but the lower range was considered outside the range of realistic values and the higher range includes “inaccessible” banks that would be difficult to recover, such as foams in landfills (WMO, 2021), with higher estimates of 2,568 kilotonnes of CFC-11 (not including unexpected) and CFC-12 banks of 2,900 ODP-weighted kilotonnes (Lickley et al., 2020).</p> <p>A high-end range for potential HFC offsets can be estimated from a scenario where emissions from new production and banks ceased in 2023, which would reduce cumulative emissions by 32–37 GtCO₂e relative to the Kigali Amendment schedule (Liang et al., 2022).</p>
Replace inefficient air conditioners (ACs) with super-efficient, low-GWP ACs and destroy recovered ODS and HFC refrigerants	
Reduce production and emissions of ozone-depleting GHGs not controlled under the Montreal Protocol (i.e., N ₂ O or	<p>Industrial emissions were 307 kt N₂O (84 GtCO₂e) from adipic acid and 136 kt N₂O (37 GtCO₂e) from nitric acid</p>

CH ₂ Cl ₂) or GHGs not controlled under the Montreal Protocol (i.e., CH ₄)	production in 2020; U.S. EPA estimates 80% abatement potential at break-even costs (Davidson and Winiwarter, 2023).
Increase the energy efficiency performance of building air conditioning and residential, commercial, and industrial refrigeration together with ODS and HFC transitions	Cumulative energy-related CO ₂ emissions for cooling for 2023-2050 could be reduced by 47–69% through improved energy efficiency, while transitioning to low-GWP refrigerant would add a further 25–53% reduction in CO ₂ e terms (TEAP, 2023a).

240 Others have implicitly suggested the usefulness of offsets: “The recovery and destruction of CFC-11 banks would not only accelerate the ozone layer recovery, but also yield climate benefits (WMO-~~6~~, 2021). Based on the TEAP/UNEP (2019b) scenario, recovery and destruction of the active and inactive banks would reduce emissions by 1.6 Gt CO₂-eq [~~100-yearGWP₁₀₀~~; 2.2 GtCO₂-eq ~~20-yearGWP₂₀~~] between 2020 and 2060 and 2.6 Gt CO₂-eq [~~100-yearGWP₁₀₀~~; by 3.6 GtCO₂-eq ~~20-yearGWP₂₀~~] between 2020 and 2100 (see Table 5.2). Using their estimates of much larger banks, Lickley et al. (2020) estimated that

245 recovery and destruction of the CFC-11 and CFC-12 banks would reduce emissions by 9 Gt CO₂-eq [~~100-yearGWP₁₀₀~~; 13 Gt GtCO₂-eq ~~20-yearGWP₂₀~~] between 2020 and 2100.” Recent analysis by (Lickley et al., 2022) suggests that production may have been underreported for nearly all chemicals examined, implying larger banks, and they conclude that “in terms of climate impacts, CFC-11, CFC-12, and HCFC-22 are the largest banked materials weighted by GWP₁₀₀, accounting for 36 %, 14 %, and 36 % of current [ODS] banks, respectively. When banks are weighted by ODP, CFC-11 and CFC-12 represent 46 % and

250 halons also represent 46 % of current banked chemicals.... In terms of GWP₁₀₀, CFC-11 banks largely reside in foams, whereas CFC-12 and HCFC-22 are largely in non-hermetic refrigeration. The latter may be more readily recoverable. In terms of ODP, CFC-11 foams and CFC-12 non-hermetic refrigeration remain important, along with halons which are all contained in fire extinguishers, a recoverable reservoir.”³

6 Conclusion

255 This technical notes describes approaches for offsetting the ozone depletion and climate forcing from unexpected and unreported production and associated emissions of ozone-depleting substances (ODSs) (e.g., CFC-11, CFC-12, CFC-113, and CTC). Scientists can calculate the contribution of each option in offsetting potentially both the annual and cumulative ozone depletion and climate forcing over the atmospheric lifetime of the ODSs but we argue here that typically the most practical approach (and in some instances the only approach) will be to consider offsetting cumulative impacts without consideration

³ If an alternative is identified for those essential uses preserving health and safety, halons could be a recoverable reservoir.

260 of timing. The Montreal Protocol Parties have shown creativity and flexibility in their non-compliance remedies (UNEP, 1992).
Parties to the Montreal Protocol may wish to consider action on compliance to minimize ozone and climate consequences and
to discourage future unexpected and unreported production.

Author contribution

265 SOA conceptualized the study. GBD, SAM, SOA, RF wrote the paper.

Competing interests

The authors declare that they have no conflict of interest.

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