environmental
investigation
agency

Persistent Problems

The hidden impacts of hydrofluoroolefins, the latest generation of fluorinated gases

July 2025

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ABOUT EIA

We investigate and campaign against environmental crime and abuse. Our undercover investigations expose transnational wildlife crime, with a focus on elephants, rhinos, pangolins and tigers and forest crimes such as illegal logging and deforestation for cash crops such as palm oil. We work to safeguard global marine ecosystems by addressing the threats posed by plastic pollution, underwater noise, bycatch and commercial exploitation of whales, dolphins and porpoises. Finally, we work to avert climate catastrophe by strengthening and enforcing regional and international agreements that tackle short-lived climate superpollutants, including ozone-depleting substances, hydrofluorocarbons and methane, and advocating corporate and policy measures to promote transition to a sustainable cooling sector and away from fossil fuels. We use our findings in hardhitting reports to campaign for new legislation, improved governance and more effective enforcement. Our field experience is used to provide guidance to enforcement agencies and we form partnerships with local groups and activists and support their work through hands-on training.

OUR CLIMATE WORK

Our Climate programme seeks to keep global warming below 1.5°C and meet the climate challenge through rapid, sustained reductions of emissions of all the major greenhouse gases. This will be achieved by developing, implementing and enforcing ambitious national, regional, global and sectoral obligations to reduce emissions of ozone-depleting substances (ODS), fluorinated gases (F-gases), methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). These obligations should be reinforced by strong governance frameworks ensuring corporate accountability and sustainable financing for a just and fair transition for all.

EIA is the only NGO committed to combating HFC and ODS climate crime and has almost 30 years of experience investigating and exposing this criminal trade. Our groundbreaking investigations have helped change laws to better protect our planet. Our work also focuses on promoting rapid greenhouse gas mitigation opportunities through the uptake of climate-friendly HFC-free cooling solutions.

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CONTENTS

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Executive summary

Fluorinated gases (F-gases) have, for many decades, been used as refrigerants and in other applications such as foam blowing and fire suppression.

The first generation of F-gases were ozone-depleting chlorofluorocarbons (CFCs). These were replaced with hydrochlorofluorocarbons (HCFCs), which have a lower although still significant ozone-depleting potential (ODP). The phase-out of CFCs and HCFCs also led to the uptake of a third generation of F-gases, hydrofluorocarbons (HFCs). HFCs are potent greenhouse gases (GHGs), many of which have global warming potentials (GWPs) hundreds or even thousands of times that of carbon dioxide (CO_2).

As a result of the action taken under the Montreal Protocol, the ozone layer is recovering and emissions of climate-damaging gases are being curbed. However, as each generation of F-gases was developed, it took many years to act upon the new environmental threats they pose.

With the HFC phase-down now underway, it is important to recall this context when considering which alternatives should be used in their place. Now the fluorochemical industry is promoting a new generation of F-gases – hydrofluoroolefins (HFOs).

What are HFOs?

HFOs are unsaturated F-gases, meaning they contain a carbon-carbon double bond that is not present in previous generations of F-gases. The double bond is also present in other unsaturated halocarbons, namely hydrochlorofluoroolefins (HCFOs) and hydrobromofluoroolefins (HBFOs).

Most HFOs have reported GWP values of one or less and HCFOs and HBFOs have ODPs close to zero.

HFOs are used as refrigerants and in refrigerant blends with high-GWP HFCs. They can also be used as foam blowing agents, aerosol propellants, solvents and in some fire suppression systems. During the past decade, production, consumption and emissions of HFOs have been increasing.

HFOs have low GWP values but lead to emissions of other high-GWP and -ODP substances

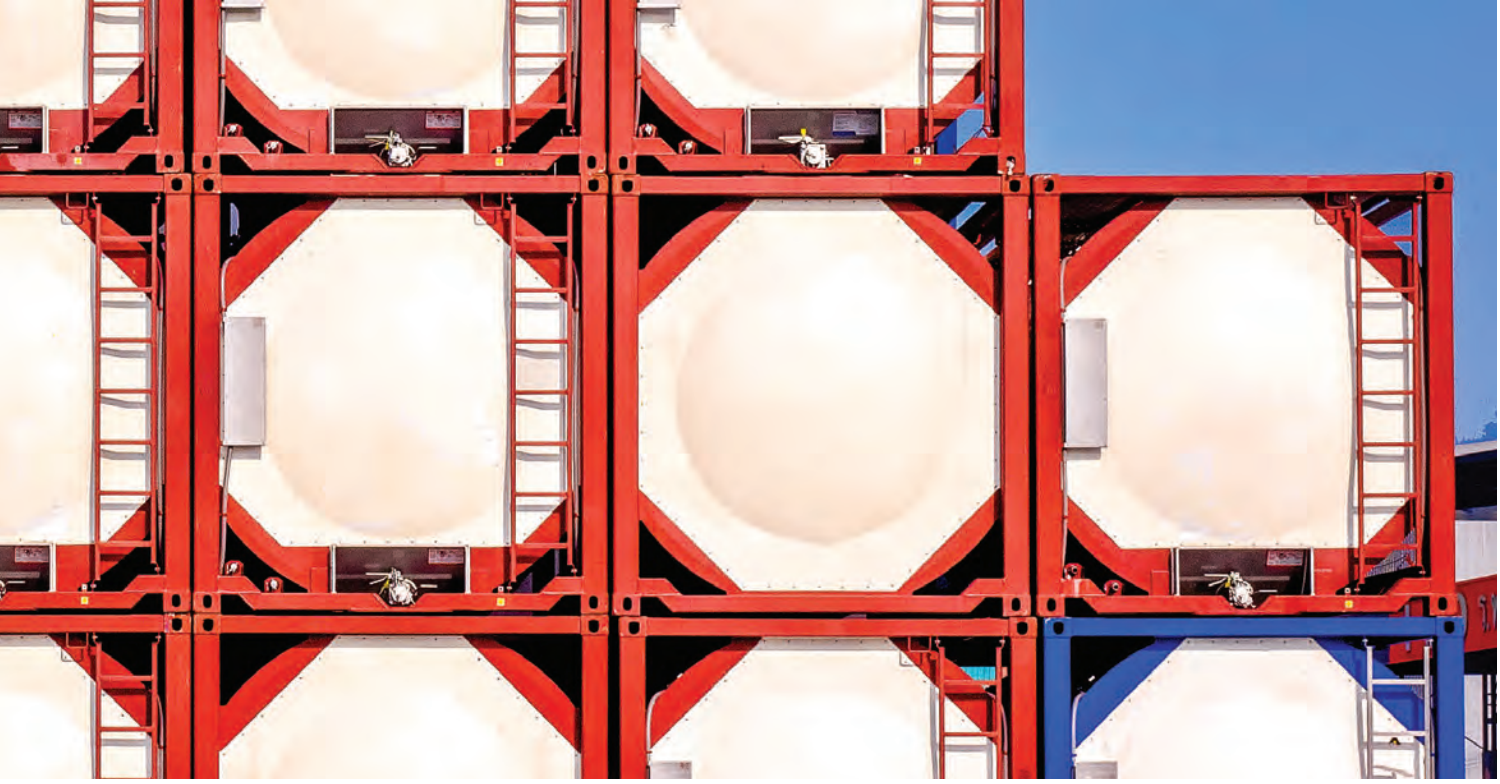
Uptake of HFOs is encouraged by the idea that these are sustainable products with little environmental impact, but despite their low GWP and ODP values, this is not the case.

In fact, HFOs do contribute, indirectly, to climate change and ozone-depletion due to emissions of high-GWP and -ODP species during HFO production and atmospheric breakdown.

HFOs are a source of persistent PFAS pollution

A common feature of all per- and polyfluoroalkyl substances (PFAS) is that they are very persistent; they are, or they degrade into, substances which are chemically stable and thus remain in the environment for very long periods of time.

Atmospheric breakdown of many common HFOs and some other F-gases results in formation of the ultra-short chain PFAS, trifluoroacetic acid (TFA). The available evidence indicates TFA has low levels of toxicity at environmental concentrations, but there are



crucial gaps in the evidence. There is also the potential for unknown effects in the future, for example due to chronic exposure or effects occurring in mixtures.

There is ongoing debate within the scientific community about the risks posed by TFA. However, given the irreversible nature of TFA pollution, the ongoing debate must not prevent immediate action. A precautionary approach, which restricts the use of HFOs and avoids unnecessary risks to people and the environment, is required.

HFOs also come with economic, trade and governance issues

HFOs are typically the patented products of large multinational chemical companies and they tend to be more expensive than HFCs and HCFCs. Uptake of HFOs has also been hampered by supply problems.

HFOs are often used in blends with HFCs. This prolongs the production and use of high-GWP HFCs and can create additional challenges for management of refrigeration equipment. As drop-in replacements for HFCs, there is a risk of illegal HFC use during the servicing of equipment.

In recent years, illegal HFC imports have been labelled as HFOs, presenting new enforcement challenges.

Non-fluorinated alternatives are available for most F-gas applications

The transition away from HCFCs and HFCs is of utmost importance, but the uptake of HFOs can be avoided by instead replacing HFCs with not-in-kind technologies or non-fluorinated alternatives, which are already available for most of F-gas applications.

Some of the tactics and arguments used to promote HFOs echo those made prior to the phase-out of previous generations of F-gases or other PFAS.

Unfavourable evidence is being questioned or ignored, a lack of consensus about the risks is being used to delay action and the discussion is distorted by misleading or exaggerated claims about the sustainability or viability of non-fluorinated alternatives.

The precautionary principle must be applied to avoid unnecessary risks to people and the planet

There are evidence gaps and uncertainties when it comes to the use and impacts of HFOs and more research is urgently needed, but this must not be used as a reason to delay action. If HFOs significantly increase in use, the presence of these chemicals and their breakdown products will become widespread in the environment and will become increasingly difficult to address.

EIA urges all governments and parties to the Montreal Protocol to apply the precautionary principle, wherever possible avoiding the uptake of HFOs to avoid unnecessary risks to people and the planet. Governments, parties to the Montreal Protocol and manufacturers and commercial users of these products must act to implement a transition away from all F-gases.

Introduction

Fluorinated gases (F-gases) have, for many decades, been used as heat transfer agents (ie, refrigerants) in cooling and heating and in other applications such as foam blowing and fire suppression.

After it was discovered that the first generation of F-gases, CFCs, were causing significant damage to the ozone layer, countries around the world came together to take action. The Montreal Protocol on Substances that Deplete the Ozone Layer was adopted in 1987 and, as a result, the primary use of CFCs in products and equipment has been phased out around the world.[1] Initially, CFCs were replaced with HCFCs, which were intended as transitional substances with lower, although still significant, ODP.[2] The phase-out of CFCs and HCFCs also led to uptake of a third generation of F-gases, HFCs. Although HFCs are not ODS, they are potent GHGs, many of which have GWPs hundreds or even thousands of times that of CO_2.[3]

Recognising the climate threat posed by HFCs, in 2016 parties to the Montreal Protocol adopted the Kigali Amendment, under which the consumption and production of HFCs will be phased down to about 15-20 per cent of current levels.[4]

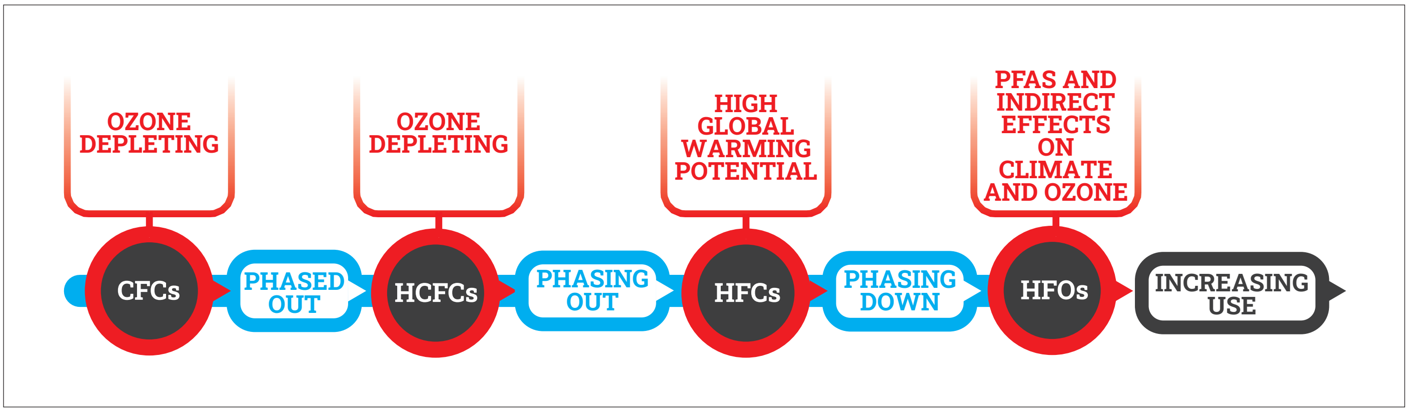
As a result of the action taken under the Montreal Protocol, the ozone layer is recovering and emissions of climate-damaging gases are being curbed.[5] However, as each generation of F-gases was developed, it took many years to act upon the new environmental threats they pose. With the HFC phase-down now under way, it is important to recall this context when considering which alternatives should replace them.

This report focuses on the new generation of F-gases being promoted by the fluorochemical industry – unsaturated halocarbons, known as hydrofluoroolefins (HFOs).

Producers of HFOs claim these are sustainable products[6] and while it is true they have lower GWP and ODP than previous generations of F-gases, they still pose unnecessary risks to public health and the environment. Non-fluorinated alternatives are already available for most F-gas applications, thus there is no need to repeat history by transitioning to yet another generation of fluorochemicals. Instead, it is time to put people and the planet first and finally break free from F-gases.

Although this report is focused on HFOs, a similar precautionary principle should be applied to the use of other fluorinated compounds being used as ODS or HFC replacements, such as perfluorocarbons (PFCs) and hydrofluoroethers (HFEs).

Figure 1: *Generations of damaging F-gases*



Source: EIA

What are HFOs?

HFOs are F-gases containing a carbon-to-carbon double bond, which is not present in saturated halocarbons such as HFCs and HCFCs. The double bond is also present in other unsaturated halocarbons, namely HCFOs and HBFOs.

The presence of the carbon-carbon double bond increases reactivity, causing HFOs and other unsaturated halocarbons to break down rapidly in the atmosphere. Their short atmospheric lifetimes, usually a matter of days, mean that the direct climate and ozone impacts of these chemicals are lower than for longer lived saturated halocarbons.[7] As such, many HFOs have reported GWP values of one or less, while HCFOs and HBFOs, which are examples of a group of compounds known as very short-lived substances (VSLS), have ODPs close to zero (see Table 1).[8]

The increased reactivity imparted by the double bond also means that some HFOs, such as HFO-1234yf and HFO-1234ze(E), are flammable, although the presence of the chlorine or bromine modulates this effect in HCFOs and HBFOs (see Appendix).[9]

Above: A HFO-1234yf car air-conditioning recharging system.

The main use of HFOs is as refrigerants and they are often used in refrigerant blends with high-GWP HFCs to achieve the desired properties.[10] For example, refrigerant R-452A (GWP 2,336) is a blend of HFC-125 (GWP 3,820), HFC-32 (GWP 749) and HFO-1234yf (GWP <1).[11] HFOs can also be used as foam blowing agents, aerosol propellants and solvents and in some fire suppression systems (see Table 1).

In developing countries (referred to as Article 5, or A5, countries in the context of the Montreal Protocol), the HCFC phase-out is ongoing and the phase-down of HFCs is just beginning (with the level of permissible HFC consumption now capped in most countries).[12] However, in developed (non-Article 5, or non-A5) countries, the HFC phase-down mandated under the Kigali Amendment is already under way.[13] HFOs are not controlled under the Montreal Protocol and in many non-A5 countries the policies that are in place to govern the transition from HFCs incentivise the use of HFOs, alongside other lower-GWP alternatives.[14] Considering this, it is unsurprising that during the past decade, production, consumption and emissions of HFOs have been increasing.[15]

Uptake of HFOs is encouraged by the idea that these are sustainable products, with little environmental impact. However, despite their low GWP and ODP values, this is not the case.

In fact, HFOs do contribute, indirectly, to climate change and ozone-depletion due to emissions of high-GWP and -ODP species during HFO production and atmospheric breakdown. They are also a source of PFAS pollution and come with other environmental, health and societal risks.

Table 1: *Commonly used HFOs and HCFOs. See Appendix Table A1 for more detail.*

HFO	Main uses	Production[16]	Direct climate/ ozone impact[17]	Atmospheric breakdown to HFC-23	PFAS[18]
HFO-1234yf $CF_3CF=CH_2$	Refrigerant and HFC-HFO refrigerant blends (eg, R-454C, R-454A, R-455A, R-449A, R-513A)[19]	Produced from HCFC-22 feedstock (ODP 0.038) (with byproducts including HFC-23 (GWP 14,700) and PFC-318 (GWP 10,600)) or from CTC (ODP 0.87) feedstock.[20]	GWP <1	No	Yes. TFA yield 100%.
HFO-1234ze(E) trans-$CF_3CH=CFH$	Refrigerant and HFC-HFO refrigerant blends (eg, R-448A),[21] aerosol propellant,[22] and foam blowing agent[23]	Produced from vinyl chloride and CTC (ODP 0.87) feedstocks.[24]	GWP 1	Yes[25]	Yes. Estimated TFA yield 2%, with an upper limit of ~ 30%.
HFO-1336mzz isomers $CF_3CH=CHCF_3$	Refrigerant,[26] fire supressant,[27] and foam blowing agent[28]	Produced from CFC-113a feedstock (ODP 0.73).[29]	Cis/ Z isomer GWP 2, Trans/ E isomer GWP 26	Yes[30]	Yes. Estimated TFA yield 4%, with an upper limit of ~ 60%.
HCFO-1233zd(E) trans-$CHCl=CHCF_3$	Refrigerant,[31] foam blowing agent,[32] and precision solvent[33]	Produced from vinyl chloride and CTC (ODP 0.87) feedstocks.[34]	OPD <0.0004, GWP 4	Yes[35]	Yes. Estimated TFA yield 2%, with an upper limit of ~ 30%.
HFO-1132a[36] $CF_2=CH_2$	Feedstock[37] and refrigerant and HFC-HFO refrigerant blends (eg, R-468A, R468B, R-468C, R-473A)[38]	Produced from HCFC-142b (ODP 0.057), HCFC-132b (ODP 0.038), or HFC-143a (GWP 5,900).[39]	GWP <1	No	No

Increasing consumption, production and emissions

In the absence of public reporting requirements, it is extremely difficult to estimate global HFO production and consumption.

Nonetheless, the available data shows that as some parts of the world begin to move away from HFCs, the production, consumption and emissions of HFOs have been increasing, as have the number of HFO-related patents.[40]

Consumption
To date, increases in consumption have predominantly occurred in non-A5 countries, such as the USA, Japan and Europe.[41]

In the USA alone, the HFO and HCFO market was estimated to be approximately 40 kilotonnes (kt) in 2021 and this is projected to more than double to 106kt in 2030.[42]

The US Environmental Protection Agency (US EPA) noted that the lack of market data makes such projections challenging and that future demand will likely increase beyond what is reported or modelled.

Production
Production of HFOs has increased significantly since 2011, at which time the US was the only commercial producer.[43] In 2022, the US EPA identified a total of 16 HFO or HCFO production sites globally, located in the US, China, India and Japan.[44] Most of these facilities are operated by, or in partnership with, US multinationals Arkema, Chemours and Honeywell (see Fig 2).[45]

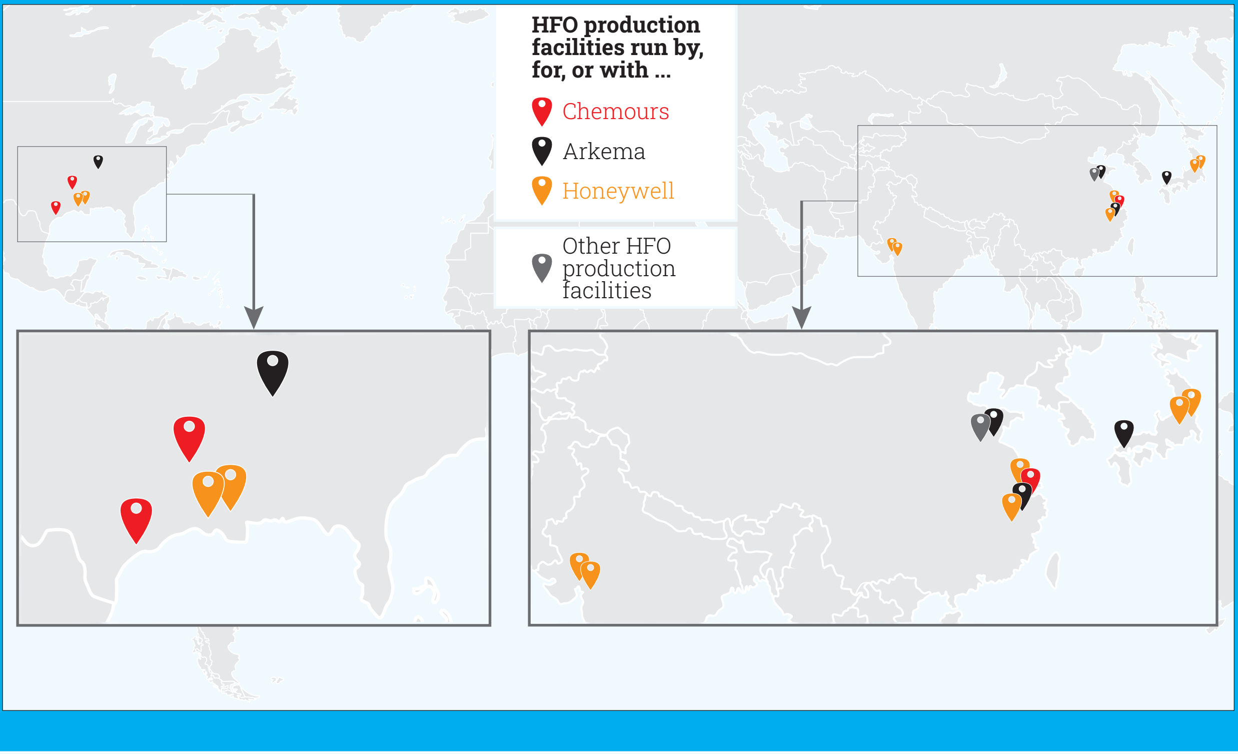
Although HFOs and HCFOs comprise an estimated 26 per cent of the EU total supply of F-gases, there appears to be no production in the region, with the EU importing primarily from the US and China.[46]

HFO-1234yf accounts for the majority of global HFO production.[47] The main markets for HFO-1234yf are in Europe and the US, where it is widely used in refrigerant blends for stationary refrigeration and air-conditioning and, in its pure form, in mobile air-conditioning (MAC) for passenger vehicles.[48] As of 2023, HFO-1234yf use in the US has expanded to 97 per cent of new vehicles.[49]

Emissions
As production and use of HFOs and HCFOs has increased, so have emissions of these chemicals to the atmosphere.

Their short atmospheric lifetime makes it challenging to use atmospheric measurements to estimate global emissions, but regional monitoring in Europe has demonstrated increased emissions of HFO-1234yf and HFO-1234ze(E).[51]

Figure 2: *HFO and HCFO production facilities identified in 2022 by the US EPA.*[50]



Indirect climate and ozone impacts

Production-related emissions

The production of many HFOs involves ODS and HFCs, which are used as feedstocks, process agents or intermediates, or which arise as byproducts (see Table 1).[52]

The use of ODS and HFCs in the production of fluorochemicals such as HFOs and fluoropolymers is not controlled under the Montreal Protocol, but is coming under increased scrutiny from the parties based on concerns about growing feedstock- and production-related emissions.[53]

These emissions can be significant and there are numerous evidenced cases of feedstock and byproduct emissions being underreported.[54]

Despite this, discussions relating to the climate and ozone impacts of HFOs often ignore the contribution of production-related emissions to ozone layer depletion and increased radiative forcing.

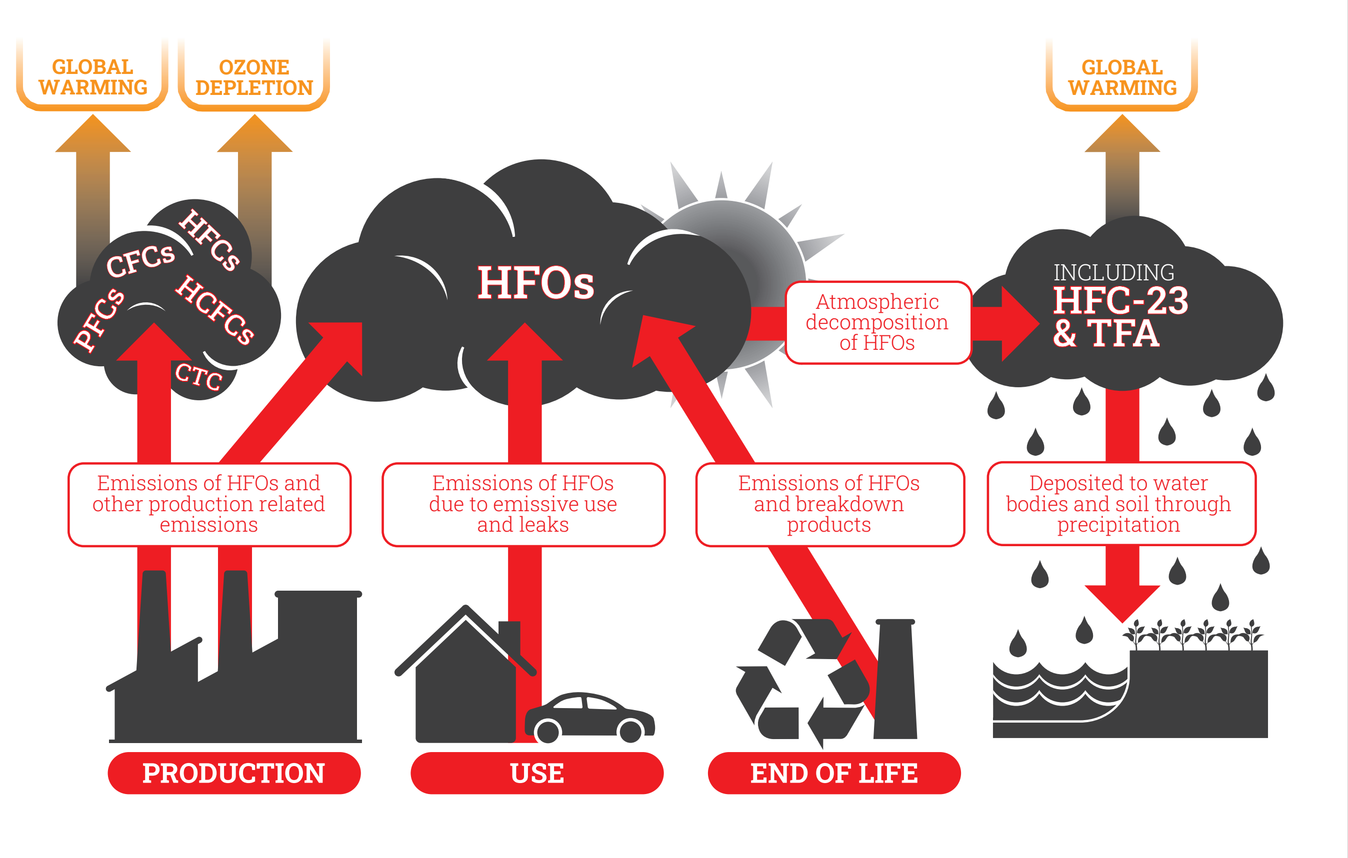
Based on the available information concerning HFO production pathways, emissions of a variety of ODS (such as carbon tetrachloride (CTC), HCFC-22 or CFC-113a) and high-GWP substances (such as HFC-23 or PFC-318) can be expected (see Table 1).[55] Of particular concern are emissions of CTC, an ODS (ODP = 0.87) used in the synthesis of many HFOs, including HFO-1234yf.[56]

Increasing demand for HFOs has already contributed to a growth in CTC production in recent years[57] and, if demand continues to increase, this could result in sustained elevated atmospheric abundance of this damaging ODS.[58]

Based on current publicly available information, it is not possible to accurately quantify the ozone and climate impacts of production-related ODS and HFC emissions. These emissions are not captured by ODP or GWP values and so a more holistic approach, such as lifecycle assessment (LCA), is required.

There are already some LCA studies on HFOs, most often in the form of lifecycle climate performance (LCCP) studies on heating or cooling systems.[59] Although LCCP studies should include refrigerant manufacturing emissions, most just refer to refrigerant manufacturing factors from earlier publications. The assumptions underlying these figures for refrigerant manufacturing emissions, such as which feedstocks were used or

Figure 3: *Environmental impacts during the lifecycle of HFOs*



Source: EIA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Lifecycle assessment

Quantification of the environmental impacts of HFOs and comparison with alternatives can be achieved using LCAs.[63] An LCA involves calculating the total emissions (direct and related to energy consumption) across the lifecycle of a product (ie, production, use and end-of-life, or the specific parts of the lifecycle within scope of the study). It often focuses on climate impacts but can also be used to determine other lifecycle environmental impacts such as ozone depletion.[64]

For heating and cooling systems, a specific approach known as LCCP has been developed. LCCP calculates the climate performance (e.g., kgCO_2 equivalents per kg product) by combining the direct emissions (refrigerant leaks during use and at end-of-life) and the indirect emissions (those associated with energy use, product disposal and production of the system and the refrigerant).[65]

Poor data availability, stemming in large part from a lack of transparency and public information about F-gas production processes, is a key challenge for those carrying out LCA or LCCP for HFOs or HFO-based systems.[66]

which emissions factors applied, are often unclear. In some instances, it is evident that they are outdated and do not reflect current manufacturing processes.[60]

Up-to-date LCA studies on HFO production are needed and these should consider ozone depletion as well as climate metrics.[61] Quantification is to some extent limited by lack of publicly available data on industrial processes, although estimated emission factors can give some indication of the emissions that might be expected. For example, the Montreal Protocol's Technology and Economic Assessment Panel (TEAP) estimates that for the production, distribution and use of ODS and HFC feedstocks, emission factors are between 1.5-6.1 per cent, relative to the mass of feedstock produced.[62]

Although further quantification is needed, the use of longer-lived, high-ODP and GWP substances in HFO production risks perpetuating production and emissions of these damaging fluorochemicals. The impacts of HFO production must, therefore, be considered when comparing HFOs to low-GWP, non-fluorinated alternatives.

Atmospheric breakdown

HFOs are emitted into the atmosphere at various points throughout their lifecycle (see Fig 3). Once in the atmosphere, they break down rapidly through reactions with other substances. The main route by which HFOs break down is reaction with hydroxyl (OH) radicals.[67]

This reaction leads to the formation of fluorinated carbonyls and acids, such as trifluoroacetic acid (CF_3COOH, TFA) (discussed in more detail below) and trifluoroacetaldehyde (CF_3CHO). Trifluoroacetaldehyde, which is formed from HFOs such as HFO-1234ze(E) and HCFO-1233zd(E), as well as certain HFCs, undergoes further reactions.[68]

Reaction products can include hydrogen fluoride (HF), CO_2 and TFA, but also the potent and long-lived GHG HFC-23. The formation of small amounts of HFC-23 from trifluoroacetaldehyde has been demonstrated in numerous laboratory studies.[69] Some HFOs also form HFC-23 via the direct reaction with ozone (O_3), although this reaction is slow and accounts for only a minor portion of HFO breakdown.[70]

Atmospheric breakdown of F-gases, including but not limited to HFOs, is estimated to release up to 215 tonnes of HFC-23 per year.[71] The contribution from HFOs is uncertain, due to ongoing questions about the yield of HFC-23 production and the scale of HFO emissions, although it will increase as HFO emissions increase.

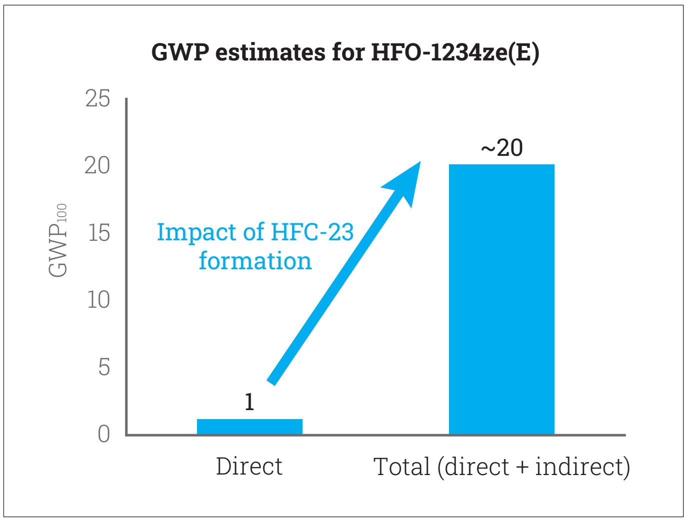
While atmospheric breakdown accounts for a very small portion of the current global HFC-23 emissions,[72] any additional release into the atmosphere should be avoided given the high-GWP value for HFC-23 (GWP 14,700) and the urgency of the climate crisis.

For individual HFOs, the impact can be quantified through a GWP calculation which takes into account the effect of the HFC-23 formed.[73] Initial attempts to do this show that the formation of even small amounts of HFC-23 increases the GWP of HFOs (see Fig 4).[74]

Further research is needed to quantify HFO emissions and refine the estimates for HFC-23 production, but also to investigate production of other ozone-depleting or climate-damaging substances from HFOs, HCFOs and HBFOs in the atmosphere.[75]

Despite the ongoing uncertainties, what is known about the climate impacts of atmospheric breakdown of HFOs further undermines the notion that they are climate-friendly products.

Figure 4: *Direct and indirect contribution to the GWP of HFO-1234ze(E). The indirect contribution is a coarse estimate from Thomson et al., which includes the impact of HFC-23 production.*[76]



Source: EIA

Other environmental and health impacts

HFO production

The fluorochemical industry is no stranger to scandals about the health impacts of its products and facilities.[77] Although to date less attention has been paid to the health impacts of F-gas production, the available evidence further supports the argument that F-gases should be avoided wherever feasible.

In 2022, a US EPA report highlighted the health risks for communities living near F-gas production facilities, including several facilities producing HFOs.[78] The health risks relate to emissions of toxic halogenated feedstocks and byproducts, such as CTC, HF and vinyl chloride. The US EPA also carried out an initial environmental justice analysis, which seemed to indicate increased cancer and respiratory risk in nearby communities.[79]

In addition to the health risks associated with HFO production facilities, there are also environmental concerns relating to the mining of fluorite, the mineral which serves as the source of fluorine for the fluorochemical industry.[80]

Contribution to persistent PFAS pollution

The Organisation for Economic Co-operation and Development (OECD) defines PFAS as substances which contain at least one fully fluorinated carbon atom (CF_3 or CF_2) without any hydrogen, chlorine, bromine or iodine atoms attached.[81] While various definitions of PFAS exist, some of which exclude F-gases,[82] under the OECD definition, many HFOs are classified as PFAS (see Table 1).[83]

PFAS are a diverse class of chemicals, with different chemical, physical and biological properties, but a common feature of all is that they are very persistent; they are, or they degrade into, substances which are chemically stable and thus remain in the environment for very long periods of time.[84] That is why they are often referred to as "forever chemicals".

Atmospheric breakdown of many common HFOs and some other F-gases results in the formation of the ultra-short chain PFAS TFA (see Table 1).[85] TFA in the atmosphere is deposited, for example, via precipitation, to ground level (see Fig 3). TFA is already the most abundant PFAS in the environment. It has been found in water bodies, remote ice cores, drinking water, food sources, wine and human bodies, and the levels found in the environment are rapidly increasing.[86]

There is insufficient evidence to determine if a natural source of TFA exists or not,[87] but either way, this would not explain the increasing amounts found in the environment. Instead, it is clear that the rising levels of TFA are a result of significant anthropogenic emissions, with F-gases being a major source.[88]

The most prolific HFO, HFO-1234yf, which is used widely in refrigeration and mobile air-conditioning, breaks down to TFA at 100 per cent yield, meaning it forms more TFA than the F-gases it replaces.[89] As a result, the transition from HFCs to HFOs will increase atmospheric formation of TFA and lead to higher levels in rainwater and water bodies.[90]

Total global consumption is also likely to increase in the future, making the F-gas contribution to the environmental TFA burden more significant.[91] Projections in the Montreal Protocol's Scientific Assessment Panel (SAP) 2022 Assessment Report indicate that by 2050, consumption of HFC-134a and HFO-1234yf could lead to global TFA formation of 360-540kt per year and average TFA concentrations in precipitation of 660-970ng/L.[92]

The short atmospheric lifetime of HFOs means TFA will be deposited closer to the emissions source than longer-lived F-gases and so some industrialised or highly populated areas will experience environmental concentrations significantly higher than the global average.[93]

TFA is very mobile in the environment and, like other PFAS, very persistent.[94] It is known to phytoaccumulate in plants and although it does not bioaccumulate in mammals in the way longer chain PFAS do, it has been detected at high levels in human blood.[95]

Why is persistence a problem?

As a result of increasing emissions, and due to its persistence, TFA will continue to accumulate in the environment. As environmental concentrations increase, they could surpass known thresholds for environmental or toxicological effects, but there is also a risk from so far unknown effects, such as harm caused by chronic low dose exposure or unique effects occurring from mixtures.[102]

There is always uncertainty in the prediction of adverse effects from chemicals and this is a particular issue for persistent substances such as TFA, where pollution is essentially irreversible. If it becomes apparent that TFA does have adverse environmental or health effects, these impacts cannot simply be halted by ceasing emissions, because the TFA already been emitted will remain in the environment for a long time.[103]

A perfect example of the problem of persistence is environmental contamination with the persistent, bioaccumulative and toxic PFAS perfluorooctanoic acid (PFOA). PFOA was widely used in applications such as waterproof clothing for many years, but was phased out after evidence of its health and environmental impacts came to light.[104]

However, due to its persistence, PFOA contamination in the environment is still a significant cause for concern.[105] Furthermore, it has now become clear that fluorochemical producers suppressed evidence about the toxic nature of PFOA for decades.[106]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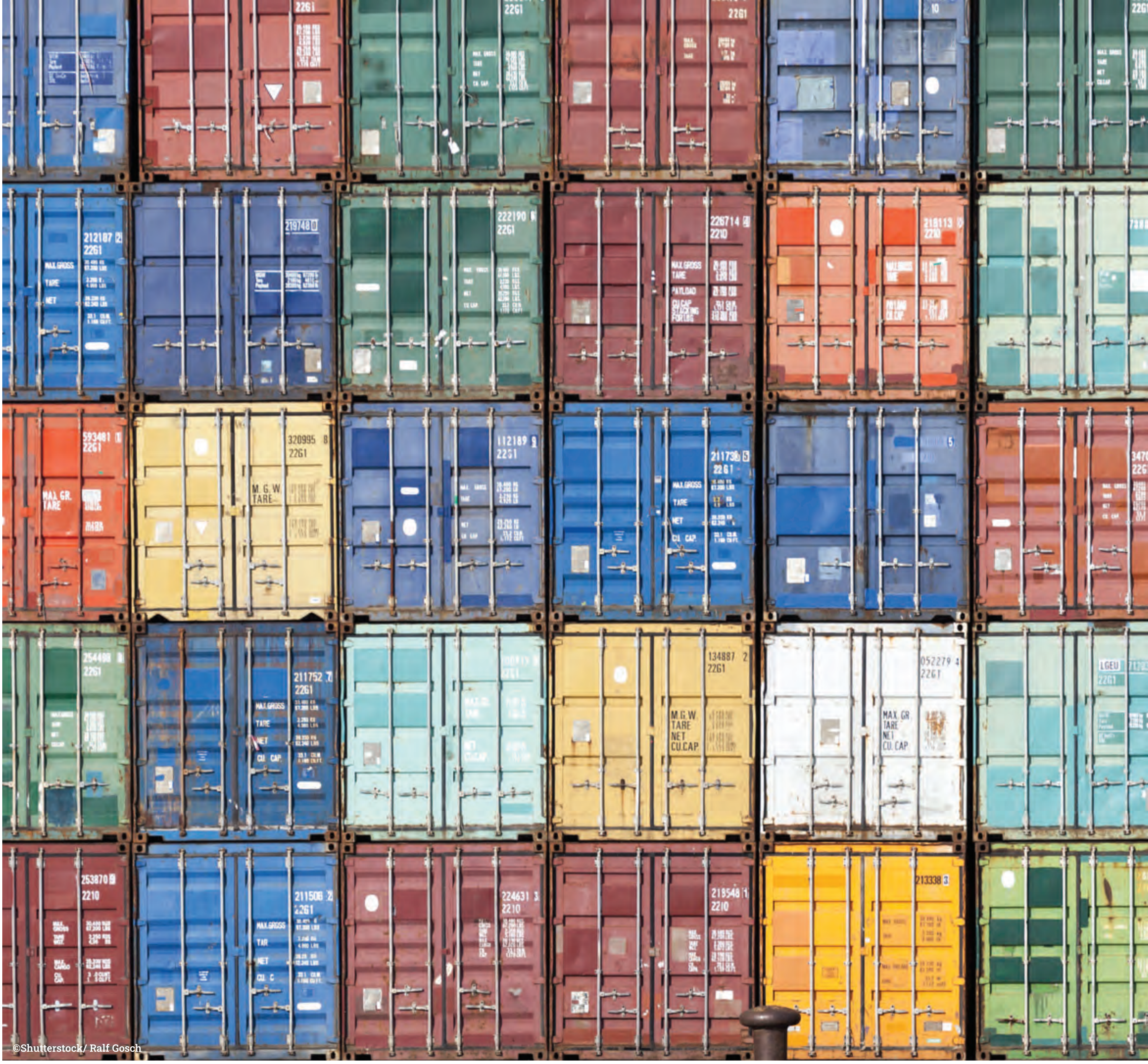
The available evidence indicates low levels of toxicity at environmental concentrations,[96] although there is evidence of reproductive toxicity at higher concentrations,[97] and there are crucial gaps in the evidence, for example, around the effects of chronic exposure.[98]

The Montreal Protocol's Environmental Effects Assessment Panel (EEAP) has concluded that TFA poses a negligible risk to human health and the environment.[99] However, many scientists disagree, arguing that even in the absence of evidence of toxicity, persistence alone is a significant cause for concern.[100] The recent 2024 EEAP update does not reflect the ongoing scientific debate around TFA, particularly with respect to its persistence.[101]

Despite the concerns about TFA raised by many in the scientific community, the fluorochemical industry continues to promote the narrative that TFA is a safe, naturally occurring substance and thus HFOs pose no risk in this regard.[107] It often omits any reference to unfavourable evidence or scientific interpretations that would bring this into question.[108] Many papers on this topic have been written, co-written or funded by the fluorochemical industry.[109]

The reality is that there are different interpretations and opinions within the scientific community on the issue of HFOs and PFAS, and more research into TFA and the consequences of the transition to HFOs is clearly required, alongside more monitoring of TFA in the environment.

However, HFOs are a source of irreversible pollution that can be avoided by a transition to non-fluorinated alternatives, and the need for more research must not prevent immediate action. A precautionary approach, which restricts the use of HFOs and avoids unnecessary risks to people and the environment, is required.



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Economic, trade and governance issues

Cost and availability

To some extent, the uptake of HFOs has been hampered by high costs and supply problems.[110]

HFOs tend to be more expensive than HFCs and HCFCs.[111] This is partly because they are still in the earlier stages of commercialisation, but they also require more complex and therefore more expensive production processes.[112]

HFOs are typically the patented products of large multinational chemical companies,[113] which also means that a few powerful stakeholders control production and price. This raises an ethical consideration for governments and members of the Executive Committee of the Montreal Protocol's Multilateral Fund (MLF) over whether expensive patented F-gases, the production of which is dominated by just a few multinational companies, should be promoted when alternatives are available.

Adoption of HFOs has been explored in a number of Kigali Implementation Plans (KIPs) and MLF-funded projects.[114] In several cases where HFOs were approved under HCFC phase-out projects, they were found to be prohibitively expensive or too difficult to obtain, and in some cases this caused manufacturing sectors which had planned to transition to HFO-based technologies to instead revert to high-GWP HFCs.[115]

HFC-HFO blends

HFOs are often used in blends with HFCs to achieve the properties required for use. This prolongs the production

and use of high-GWP species, but refrigerant blends also impact on the management of the refrigeration equipment, including its efficiency.

Blends pose additional challenges in the recovery and recycling of the refrigerant.[116] Refrigerant leaks also present greater challenges when blends are used, due to changes in composition of the remaining refrigerant that may affect its properties and performance.[117] This could lead to system owners needing to purge and refill their systems, increasing costs and the potential for emissions.[118]

Finally, there are also concerns about the quality of refrigerant blends and changes to their composition when they are moved from large isotanks to small containers used in the servicing sector, which could have significant impacts on the efficiency of the equipment using them.[119]

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Illegal trade

An additional concern is that HFOs may facilitate the illegal use of and trade in HFCs, complicating enforcement and leading to the continued use of high- GWP HFCs.

Given that HFOs and HFO blends are designed as drop-in replacements for high-GWP HFCs,[120] illegally sourced high-GWP HFCs may be used in place of the newer and more costly refrigerants to service equipment originally designed for HFOs or blends.

Refrigeration and HFC industry representatives have warned that Europe is being flooded with illegal HFC-404A (GWP 3,922) falsely marketed as HFO blends such as R-449A (GWP 1,504) and R-448A (GWP 1,497).[121] Smugglers are exploiting the fact that EU regulations are driving demand for expensive HFO blends and are offering these counterfeit refrigerants at much lower prices.

HFCs are also being smuggled into the EU through mislabelling as HFOs to avoid detection at customs.[122] HFOs benefit from reduced customs checks as they are not subject to a quota, as HFCs are, under the 2024 EU F-gas Regulation.

The lack of regulation over HFOs is a major problem for enforcement agencies that cannot check and test every shipment of HFOs.

Above: Illegal HFC-404A mislabelled as HFO-1234yf.

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Above: R-290 Heat Pump on Display at Chilventa 2024.

Alternatives to HFOs

The transition from HCFCs and HFCs is of utmost importance, but the uptake of HFOs can be avoided by instead replacing technologies using HFCs with not-in-kind technologies or those which use non-fluorinated alternatives, such as ammonia, CO_2, hydrocarbons and inert gases (e.g., nitrogen) (see Table 2). Although there is no one-size-fits-all solution, non-fluorinated aerosol propellants, solvents, foam blowing agents, fire suppressants and refrigerants are already available for most F-gas applications.[123] In fact, non-fluorinated alternatives already dominate in some sectors, where the transition to non-fluorinated substances was made as controlled ODS were phased out.[124]

In cooling and other heat transfer applications, non-fluorinated alternatives are often referred to as natural refrigerants.[125] Examples of businesses and other end users opting for natural refrigerants can be found at CoolTechnologies.org.

Natural refrigerants are widely used in heat pumps, domestic refrigeration systems, industrial cooling and commercial refrigeration, especially in the European Union, where legislation has mandated a faster, and total, HFC phase-out.[126]

The 2024 EU F-gas Regulation includes a complete ban on F-gas use in some product categories (eg domestic refrigeration from 2026, small (≤12kW) chillers from 2032 and small split air-conditioning from 2035), which will restrict the use of HFOs in certain products and so drive uptake of natural refrigerants.[127]

Non-fluorinated substances avoid many of the issues associated with HFOs (see Table 2). As well as having very low GWP values and not depleting the ozone layer, they are not a source of persistent PFAS pollution. They are not derived from high-GWP or -ODP halogenated substances and available evidence indicates that production of non-fluorinated substances such as ammonia and propane is significantly less emissions-intensive than the production of HFOs.[131]

Despite their many benefits, natural refrigerants and other non-fluorinated alternatives to F-gases do come with their own limitations and challenges, for example with regard to flammability or toxic properties.[132] Such properties must be considered when choosing the non-fluorinated substance for a particular application, but in some cases there are ways to mitigate the risks. For example, it has been shown that safety issues relating to refrigerant flammability can be effectively mitigated in many heat transfer applications through good product design, updated safety standards and a well-trained installation and maintenance workforce.[133]

Opportunities to minimise demand, even for non-fluorinated alternatives, should be considered where available. This can be pursued through system or behaviour change, or the uptake of not-in-kind solutions. For example, replacing metered dose inhalers with dry-powder inhalers can reduce demand for aerosol propellants.[134]

Similarly, passive cooling reduces the cooling load, minimising demand for both refrigerants and energy. Passive cooling can be achieved through innovative building design and construction as well as by incorporating shade and trees into urban environments. It can reduce temperatures in buildings and urban environments, even in hot climates, and could decrease projected growth in cooling demand by 24 per cent by 2050.[135]

Tackling emissions from cooling requires a holistic approach, of which non-fluorinated refrigerants and passive cooling must be part (see Fig 5).

Table 2: *Examples of non-fluorinated/ natural refrigerant alternatives to F-gases. See Appendix Table A1 for more detail.*

HFO	**Uses**	**Production**	**Climate/ozone impact**[128]
Ammonia	Refrigerant (R-717)	Haber Bosch process combines nitrogen with fossil fuel derived hydrogen	GWP <<1, ODP 0
CO_2	Refrigerant (R-744), foam blowing agent, fire suppressant, and aerosol propellant	Byproduct of industrial processes	GWP 1, ODP 0
Isobutane	Refrigerant (R-600a)	From butane, a byproduct of fossil fuel refining	GWP <<1, ODP 0
Propane	Refrigerant (R-290) and aerosol propellant	Byproduct of fossil fuel refining	GWP 0.02 (indirect contributions increase GWP to ~10),[129] ODP 0
Cyclopentane	Foam blowing agent	Naphtha cracking	GWP <<1, ODP 0
Water	Refrigerant (R-718), foam blowing agent and fire suppressant	-	GWP 0.0005,[130] ODP 0
Nitrogen	Ultra-low temperature refrigerant (R-728), foam blowing agent, fire suppressant and aerosol propellant	Fractionation of liquid air	GWP 0, ODP 0
Air	Refrigerant (R-729) and aerosol propellant	-	GWP 0, ODP 0

Fluorochemical industry push-back on F-gas alternatives

The growing interest in natural refrigerants and other non-fluorinated alternatives to F-gases is a significant threat to fluorochemical industry profits.

Unsurprisingly, the industry has pushed back, muddying the water with false claims and questioning the sustainability and viability of alternatives.[136] HFOs are promoted as sustainable alternatives, even in some sectors where the transition to non-fluorinated alternatives has been successfully achieved. For example, in Canada, where approximately 93 per cent of ice rinks use non-fluorinated refrigerants, HFO blends such as R-513A (GWP 647) and R-449A (GWP 1,504) were misleadingly marketed as suitable replacements.[137]

Energy efficiency of natural refrigerant systems

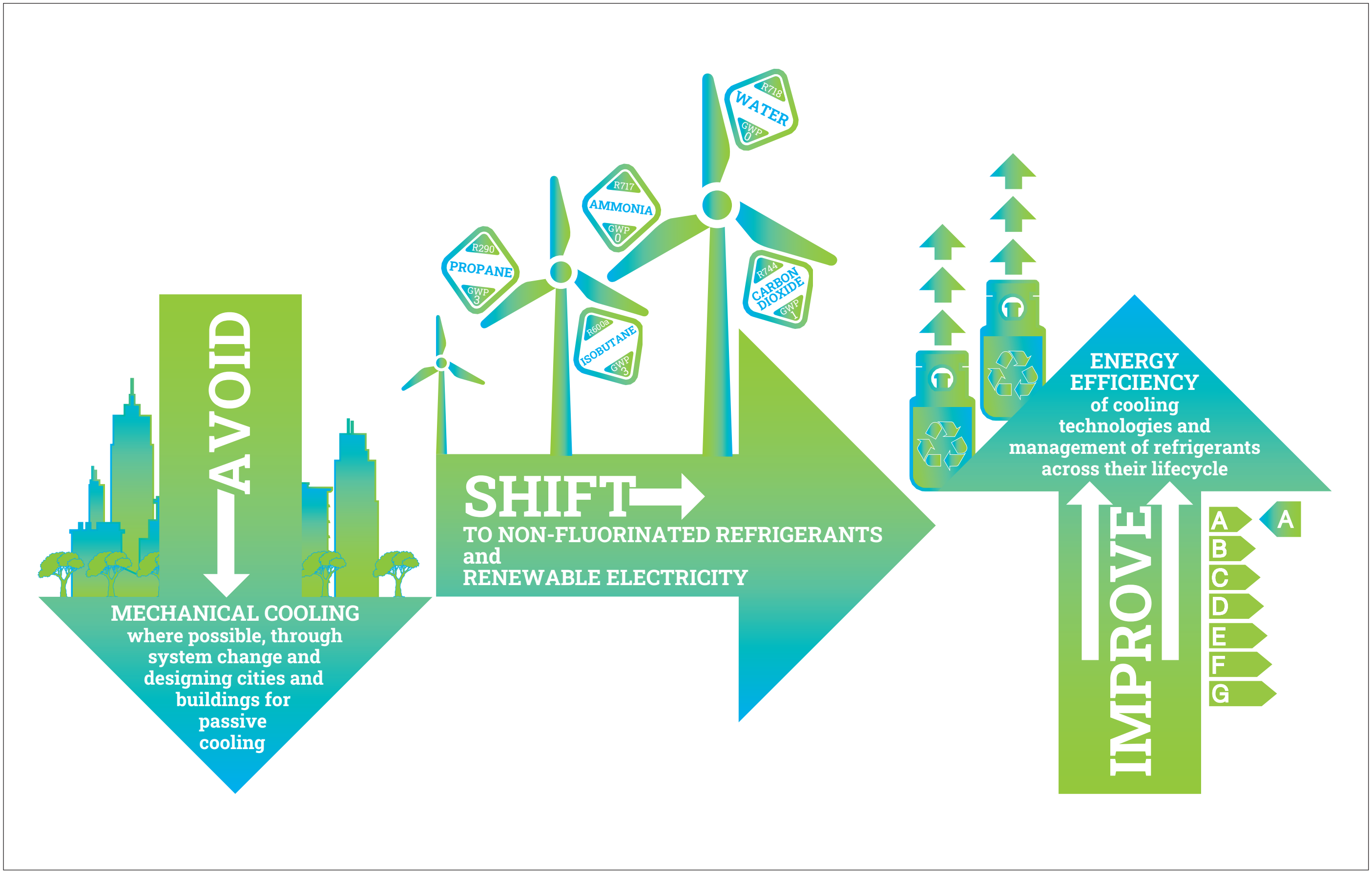
The energy efficiency of heating and cooling systems is very important because emissions related to energy use often dominate the lifecycle emissions.[138]

The fluorochemical industry often claims that natural refrigerants are less efficient than HFOs.[139] However, some natural refrigerants, such as hydrocarbons and ammonia, actually have very favourable thermodynamic properties and can outperform F-gases in terms of energy efficiency.[140] In any case, refrigerant choice generally has only a small impact on energy efficiency.[141] Of greater importance is the system design and configuration, which must be optimised for the refrigerant in question, and the effectiveness of routine cleaning and maintenance of the system.[142]

There are numerous examples demonstrating that well-designed heating or cooling systems using natural refrigerants can achieve good energy efficiency in a range of applications.[143] The transition from HFCs to natural refrigerants can come with energy efficiency improvements, even with CO_2, where the low critical temperature (about 31°C) poses challenges in high ambient temperature countries.[144]

Carrefour, the world's second-largest retailer, has reported a 7-25 per cent increase in energy efficiency after replacing F-gas systems with CO_2 refrigeration.[145]

Figure 5: *A holistic approach to cleaning up cooling*



Source: EIA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Implementing the transition away from F-gases

The transition away from HFCs and HCFCs is driven by commitments under the Montreal Protocol and the national regulations that countries put in place to meet those commitments.

HFOs are not controlled under the Montreal Protocol and in many cases are indirectly incentivised, rather than controlled, by national F-gas regulations.[146]

Additional measures will be required if countries are to transition away from all F-gases, including HFOs. This could take the form of demand-side action to encourage use of non-fluorinated alternatives and not-in-kind solutions (such as incentives or public procurement policies), measures to enable safe use of non-fluorinated alternatives in more applications (such as safety standards or training) or policies that limit the use of HFOs (such as bans on HFO-based equipment).

Some examples are found in the updated 2024 EU F-gas Regulation, which includes a world-first HFC phase-out but also mandatory training and certification of technicians on natural refrigerants and a complete ban on F-gas use (including HFOs) in some product categories in the future.[147]

Some HFOs may also be subject to control under PFAS regulations in future; class-based approaches to PFAS regulation are being explored in the EU, Canada and some US states.[148]

In A5 countries, the approach is to some extent influenced by the assistance received through the MLF.

To date, the MLF has approved a number of KIPs that rely on HFOs and funded several HFO-based projects. The MLF could instead prioritise the transition away from all F-gases and support a strategic approach to the HFC phase-down which would enable A5 countries to leapfrog directly to non-fluorinated alternatives and non-in-kind solutions, thus limiting the number of transitions required.

Funding could be prioritised for projects based on non-fluorinated alternatives or not-in-kind solutions, or additional funding incentives could be offered for countries proposing to leapfrog to these technologies in their KIPs.

So far, this approach has been avoided because the Executive Committee of the MLF is traditionally guided by a principle of “technology neutrality”. However, the precautionary principle is a cornerstone of the Montreal Protocol and in this context a “technology neutral” approach should consider the climate and ozone impacts of HFOs and the contribution to irreversible PFAS pollution, as well as the challenges faced by A5 parties in terms of supply, cost and availability.

Currently, the MLF is funding conversions in developing countries from HCFCs and HFCs to non-controlled substances. The MLF typically funds the incremental capital costs and operating costs of the conversions, but operating costs are usually only funded for one or two years.[149]

While the upfront capital costs of a conversion to a natural refrigerant may be higher than the HFO alternative which has been designed to be closer to the HFC it is replacing, the ongoing operating costs, which quickly become the responsibility of the developing country, are usually much lower.

Above: View of the room at MoP35.

Conclusion and recommendations

Despite claims that HFOs are environmentally friendly products, they contribute to persistent chemical pollution and come with both climate and ozone risks.

HFOs also prolong the production and use of high-GWP HFCs and complicate enforcement. The successful phase-out of HCFCs and HFCs must be achieved, but the availability of non-fluorinated alternatives to F-gases in many sectors provides an opportunity to break the pattern of transitioning from one generation of F-gases to another.

Some of the tactics and arguments being used to promote HFOs echo those made prior to the phase-out of previous generations of F-gases or other PFAS.[150] Unfavourable evidence is being questioned or ignored, lack of consensus about the risks is being used to delay action and the discussion is distorted by misleading or exaggerated claims about the sustainability or viability of alternatives.

There are evidence gaps and uncertainties and more research is urgently needed, but this must not be used as a reason to delay action.

EIA urges all governments and parties to the Montreal Protocol to apply the precautionary principle wherever possible, avoiding the use of all F-gases, including HFOs, to avoid unnecessary risks to people and the planet.

Recommendations for national and regional governments

- Implement ambitious policies to restrict the use of F-gases, including HFOs, where viable not-in-kind technologies or technologies based on non-fluorinated alternatives exist
- Implement policies and demand-side measures to encourage and enable the use of non-fluorinated alternatives to F-gases and not-in-kind solutions. This can include advancing adoption of standards and codes and aligning market-based incentives such as ecolabels, green building standards and equipment rebates
- Adopt a class-based approach to PFAS regulation and phase out the use of all PFAS, including F-gases and TFA precursors

- Expand mandatory reporting on F-gases to encompass HFOs
- Include HFOs within licensing systems covering HFCs and encourage their consideration in risk profiling by customs and other enforcement agencies
- Crack down on corporate greenwashing and misleading claims about the sustainability of F-gases compared to non-fluorinated alternatives
- Support independent scientific research into the environmental and health impacts of HFOs, more robust lifecycle accounting of production-related and other upstream emissions and research that will support the safe and sustainable use of non-fluorinated alternatives and not-in-kind solutions

Recommendations for Parties to the Montreal Protocol

- Request additional information on the environmental impacts of HFOs and availability of alternatives from TEAP, SAP and EEAP in their 2026 Assessments and encourage a co-ordinated and evidence-based approach across the panels
- Ensure that the TEAP, SAP and EEAP include representatives with appropriate expertise to address the issue of PFAS and TFA. To ensure transparency, up-to-date and detailed disclosure of interest declarations should be available for all members of all assessment panels
- Reexamine the feedstock exemption and take steps to address production-related emissions of high-GWP and -ODP controlled substances, including those emitted during the manufacture of HFOs
- Include HFOs in best-practice licensing systems and encourage voluntary reporting of consumption and use across sectors
- Prioritise MLF funding for projects transitioning directly to non-fluorinated alternatives or not-in-kind solutions and initiate discussions on potential demand-side measures that can be funded by the MLF to incentivise clean cooling solutions

Recommendations for private sector/manufacturers and end users

- Adopt non-fluorinated alternatives or equipment transition plans where equipment is already demonstrated and commercially available
- Engage with policymakers and other industry stakeholders, in particular the installation and servicing sector, to work toward removing market barriers to adoption of non-fluorinated alternative equipment in regions or applications where options are limited
- Support research and transparency into lifecycle impacts of HFO and HCFO alternatives in corporate accountability reports and greenhouse gas accounting standards, particularly full Scope 3 accounting for HFO and HFC production emissions of high-GWP feedstocks and byproducts.

Appendix

Table A1: *Commonly used HFOs and non-fluorinated alternatives.*

Substance	Main uses	Production
HFOs		
HFO-1234yf $CF_3CF=CH_2$	**Refrigerant**[154] eg, mobile vehicle air-conditioning (particularly passenger vehicles, some light commercial), and refrigerated transport containers and in HFC-HFO refrigerant blends (eg, R-454C, R-454A, R-455A, R-449A, R-513A)	Produced from HCFC-22 feedstock (ODP 0.038) (with byproducts including HFC-23 (GWP 14,700) and PFC-318 (GWP 10,600) or from CTC (ODP 0.87) feedstock.[155]
HFO-1234ze(E) trans- $CF_3CH=CFH$	**Foam blowing agent**[156] **Refrigerant**[157] eg, industrial/ commercial refrigeration and heat pumps, and in HFC-HFO refrigerant blends (eg, R-448A) **Aerosol propellant**[158] eg, technical and consumer aerosols, in HFC-HFO blends and being developed for MDIs	Produced from vinyl chloride and CTC (ODP 0.87) feedstocks.[159]
HFO-1336mzz isomers $CF_3CH=CHCF_3$	**Refrigerant**[161] eg, higher temperature heat pumps, chillers **Fire extinguisher**[162] **Foam blowing agent**[163] eg, insulation	Produced from CFC-113a feedstock (ODP 0.73).[164]
HCFO-1233zd(E) trans-$CHCl=CHCF_3$	**Foam blowing agent**[166] eg, insulation **Refrigerant**[167] eg, industrial chillers and waste heat recovery **Precision solvent**[168] eg, in aerosols and as a cleaning agent	Produced from vinyl chloride and CTC (ODP 0.87) feedstocks.[169]
HFO-1132a $CF_2=CH_2$	**Feedstock** eg, monomer used in fluoropolymer production such as for polyvinyldene fluoride (PVDF) **Refrigerant**[171] eg, in HFC-HFO refrigerant blends, including for ultra-low temperature refrigeration (eg, R-468A, R468B, R-468C, R-473A)	Produced from HCFC-142b (ODP 0.057), HCFC-132b (ODP 0.038), or HFC-143a (GWP 5,900).[172]
Non-fluorinated substances		
Ammonia	**Refrigerant (R-717)**[173] eg, industrial and commercial refrigeration, ultra-low and low temperature freezers, district heating, data centres, chillers, ice rinks, industrial heat pumps	Haber Bosch process combines nitrogen with fossil fuel-derived hydrogen.
CO_2	**Refrigerant (R-744)**[174] eg, industrial and commercial refrigeration, MAC for light duty vehicles and buses, transport refrigeration, chillers and waste heat recovery, combo (space conditioning and water heating) systems, air-conditioning, district heating, data centres, chillers, ice rinks, industrial heat pumps **Foam blowing agent**[175] **Fire suppression**[176] **Metal production**[177] **Aerosol propellant**[178]	Byproduct of industrial processes.
Isobutane	**Refrigerant (R-600a)**[179] eg, domestic refrigeration, commercial refrigeration, chillers, heat pumps	From butane, a byproduct of fossil fuel refining.
Propane	**Refrigerant (R-290)**[180] eg, air-conditioning, heat pumps, chillers, commercial refrigeration, transport refrigeration, ultra-low and low temperature freezers **Aerosol propellant**[181]	Byproduct of fossil fuel refining.
Cyclopentane	**Foam blowing agent**[183]	Naphtha cracking[184]
Water	**Refrigerant (R-718)**[185] eg, air-Conditioning, commercial and industrial refrigeration **Foam blowing agent**[186] **Fire suppressant**[187]	-
Nitrogen	**Refrigerant (R-728)**[189] eg, ultra-low temperature/cryogenics and blends **Foam blowing agent**[190] **Fire suppressant**[191] **Aerosol propellant**[192]	Fractionation of liquid air
Air	**Refrigerant (R-729)**[193] eg, ultra-low temperature **Aerosol propellant**[194]	-

Direct climate/ ozone impact[151]	Atmospheric breakdown to HFC-23	PFAS[152]	Refrigerant safety classification[153]
GWP <1	No	Yes. TFA yield 100%.	A2L - lower flammability
GWP 1	Yes[160]	Yes. Estimated TFA yield 2%, with an upper limit of ~ 30%.	A2L - lower flammability
Cis/ Z isomer GWP 2, Trans/ E isomer GWP 26	Yes[165]	Yes. Estimated TFA yield 4%, with an upper limit of ~ 60%.	A1 - No flame propagation
OPD <0.0004, GWP 4	Yes[170]	Yes. Estimated TFA yield 2%, with an upper limit of ~ 30%.	A1 - No flame propagation
GWP <1	No	No	A2 - flammable
GWP <<1, ODP 0	No	No	B2L - lower flammability, higher toxicity
GWP 1, ODP 0	No	No	A1 - No flame propagation
GWP <<1, ODP 0	No	No	A3 - higher flammability
GWP 0.02, ODP 0	No, but other indirect contributions increase GWP to ~10.[182]	No	A3 - higher flammability
GWP <<1, ODP 0	No	No	Flammable, but no refrigerant safety classification
GWP 0.0005,[188] ODP 0	No	No	A1 - No flame propagation
GWP 0, ODP 0	No	No	A1 - No flame propagation
GWP 0, ODP 0	No	No	-

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43. US EPA (2022), Global Overview of HCFC, HFC, and HFO/HCFO Production. *Ibid.*

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47. US EPA (2022), Global Overview of HCFC, HFC, and HFO/HCFO Production. *Ibid.*

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60. For example, a 2013 study from the International Council on Clean Transportation found that production of HFO-1234yf resulted in emissions of 13.5 kg CO_2e per kg product, 10.4 kg CO_2e of which was from climate-forcing chemicals released during production and the rest of which related to energy use. However, the study was carried out over 10 years ago and is based on HFO-1234yf production from CTFE, not HCFC-22 or CTC, which are now reportedly the main sources of HFO-1234yf production. It also gives no indication of the ozone impacts of HFO-1234yf production. See: The International Council on Clean Transportation, 2013. Upstream climate impacts from production of R-134a and R-1234yf refrigerants used in mobile air conditioning systems. Available here.

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73. GWP values are calculated using the infrared absorption of the molecule and its atmospheric lifetime, but they can also include the effects of degradation products.

74. Thomson *et al.* (2024), Fluoroform (CHF3) Production from CF3CHO Photolysis and Implications for the Decomposition of Hydrofluoroolefins and Hydrochlorofluoroolefins in the Atmosphere. *Ibid.*
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    Lindley, A.A. An Inventory of Fluorspar Production, Industrial Use, and Emissions of Trifluoroacetic Acid (TFA) in the Period 1930 to 1999. Journal of Geoscience and Environment Protection. Vol.11 No.3, March 2023.
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95. Arp *et al.* (2024), The Global Threat from the Irreversible Accumulation of Trifluoroacetic Acid (TFA). *Ibid.*

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101. The EEAP 2022 Assessment (EEAP (2022), Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change. *Ibid.*) dismissed the views expressed in numerous scientific publications about why TFA's persistence is a concern or what the scientific argument is for regulating PFAS as a chemical class, though there was not any real discussion of the arguments laid out in these peer reviewed publications (eg, see EEAP (2022), pg 279).
In the EEAP 2024 Update Assessment (EEAP (2024), Environmental consequences of interacting effects of changes in stratospheric ozone, ultraviolet radiation and climate. *Ibid.*), there is no discussion about the classification of TFA as PFAS, or the concerns being voiced by many scientists about its persistence. This may be because the EEAP feel they dealt with it by expressing their contrary opinion in the 2022 assessment. However, EEAP's opinion on this does not change the fact that it is an area of ongoing scientific debate in the peer reviewed literature. Between 2022 and 2025 (when the 2024 Update Assessment was published) several new peer reviewed papers that note concerns around TFA were published and there has been ongoing discussion in the scientific community. For example: Arp *et al.* (2024), The Global Threat from the Irreversible Accumulation of Trifluoroacetic Acid (TFA). *Ibid.*),
Garavagno *et al.* (2024), Trifluoroacetic Acid: Toxicity, Sources, Sinks and Future Prospects. *Ibid.*
Freeling *et al.* (2023). Assessing the environmental occurrence of the anthropogenic contaminant trifluoroacetic acid (TFA). *Ibid.*

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Kwiatkowski *et al.* (2020), Scientific Basis for Managing PFAS as a Chemical Class. *Ibid.*
Cousins *et al.* (2019), Why is high persistence alone a major cause of concern? *Ibid.*
Arp *et al.* (2024), The Global Threat from the Irreversible Accumulation of Trifluoroacetic Acid (TFA). *Ibid.*
Note that there have been some efforts to develop methods to remove TFA from contaminated water sources, but these have been found it be very costly, inefficient and technically challenging. See: Arp *et al.* (2024), The Global Threat from the Irreversible Accumulation of Trifluoroacetic Acid (TFA). *Ibid.*
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The European federation of national associations of water services (EurEau), 2025. Position Paper TFA in Drinking Water Resources. Available here.

104. Gaber, N., *et al.* The Devil they Knew: Chemical Documents Analysis of Industry Influence on PFAS Science. Annals of Global Health. 89(1), p. 37. https://doi.org/10.5334/aogh.4013.
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107. For example, none of these publications mention TFA or PFAS:
Opteon (2023), F-gases: A Critical Climate Solution. *Ibid.*
Opteon (2022), HFOs: What You Need To Know. *Ibid.*
Honeywell (2012), Low GWP hydrofluoroolefins (HFO) Reducing the impact on climate change. *Ibid.*.
The following web page states that TFA is a naturally occurring substance and does not pose a threat to humans and the environment, and does not mention the debate over natural origins, PFAS, or TFA's persistence or arguments about why that is a concern: Opteon. Natural Refrigerants: Separating Myths From Facts. Available here. [Accessed June 2025].
A Chemours "fact sheet" states that 95% of TFA is formed naturally, with no reference to the studies that brought this into question. Again there is no mention of TFA's persistence or arguments about why that is a concern, or TFA's classification as PFAS. It also claims that if all car MAC units used HFO-1234YF, it would only increase the amount of TFA in the world's oceans by 0.04% but it is unclear to EIA how this figure was calculated from the reference given. For comparison, projections in the SAP 2022 Assessment Report indicate that between 2020 and 2100 the use of HFC-134a and HFO-1234yf could substantially increase ocean TFA concentrations. See: Chemours, 2024. HFOs and TFA: Know the facts. Available here. [Accessed May 2025].

108. *Ibid.*

109. For example: Boutonnet *et al.* (1999), Environmental Risk Assessment of Trifluoroacetic Acid. *Ibid.*
Wallington *et al.* (2021), The case for a more precise definition of regulated PFAS. Environmental Science Processes & Impacts. *Ibid.* (In this case, no fluorochemical producers were involved, but one of the authors worked for a Motor company which uses HFO-1234yf).
Singh *et al.* (2021), Comment on "Scientific Basis for Managing PFAS as a Chemical Class". *Ibid.*
Luecken *et al.* (2010), Ozone and TFA Impacts in North America from Degradation of 2,3,3,3-Tetrafluoropropene (HFO-1234yf), A Potential Greenhouse Gas Replacement. *Ibid.*
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United Nations Environment Programme (UNEP), 2024. UNEP/OzL.Pro/ExCom/94/58. Paper on the issue of alternatives in polyurethane foam manufacturing. Available here.
United Nations Environment Programme (UNEP), 2025. UNEP/OzL.Pro/ExCom/96/60. Updated report on the issue of alternatives in polyurethane foam manufacturing with a focus on small- and medium-sized enterprises, in particular for spray and insulating foam applications (Decision 94/58(c)). Available here.

111. Green Cooling Initiative, 2024. High GWP Refrigerants Face Soaring Prices as Natural Alternatives Offer Stability. Available here. [Accessed May 2025].
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UNEP (2024), Paper on the issue of alternatives in polyurethane foam manufacturing. *Ibid.*

112. Sherry *et al.* (2017), HFO-1234yf: An Examination of Projected Long-Term Costs of Production. *Ibid.*

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