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Unchecked

The fluorochemical industry's scandalous HFC-23 by-product emissions amid the climate crisis

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Executive summary

Emissions of HFC-23, a potent greenhouse gas, reached a record high of 17,300 tonnes/year in 2019, equivalent to more than a quarter of a billion tonnes of carbon dioxide equivalent (254 $MtCO_2e$).

Since 2020, the Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer has required Parties to capture and destroy HFC-23, which is primarily produced and emitted as an unwanted by-product of HCFC-22, an ozone-depleting substance (ODS) controlled by the Montreal Protocol.

Before the Kigali Amendment, multiple domestic, regional and international efforts have been made to address HFC-23 emissions, starting with the Clean Development Mechanism (CDM) in 2006 and followed by domestic legislation in most major producing countries and pledges by industry to abate the emissions.

Concern over the unexpectedly high HFC-23 emissions has prompted two recent decisions by the Montreal Protocol aimed at further understanding potential emission sources as well as best practices to control them. Updated reports from the Technology and Economic Assessment Panel (TEAP) and the Scientific Assessment Panel (SAP) provide further information but fail to close the gap between top-down (atmospheric monitoring) and bottom-up (reported inventories and other evaluations) estimates.

Although the TEAP appears confident that all major sources of HFC-23 emissions have been identified, its ability to fully elucidate emissions sources is severely hampered by a significant lack of data due to industry confidentiality, as well as a plethora of monitoring and reporting inadequacies, including under-reporting of emissions recently exposed in Europe.

The atmospheric monitoring data, however, is clear – emissions from China account for up to half of the global HFC-23 emissions gap over the period 2015-22. Although emissions decreased from 2019-22, they remain higher than anticipated, underscoring ongoing compliance issues and the need for effective monitoring and regulation of the fluorochemical industry.

Cumulative HFC-23 emissions since the adoption of the Kigali Amendment in 2016 are almost 106,000 tonnes, equivalent to 1.56 billion tonnes of CO_2.[1] A strong response from the Parties to the Montreal Protocol is required.

EIA calls on the Parties to:

- request additional information from the TEAP and SAP, using expert advice where necessary and involving the Multilateral Fund (MLF) Secretariat, to resolve data reporting discrepancies and continued gaps in understanding emission sources, including a comprehensive analysis of HFC-23 emissions from the production of polytetrafluoroethylene (PTFE), hydrofluorocarbons (HFCs) and hydrofluoroolefins (HFOs)
- elaborate on approaches used by Parties when measuring and reporting HFC-23 emissions and set guidance for Article 7 reporting and verification, including defining 'extent practicable' which involves the use of storage to avoid emissions during shutdown
- take immediate steps to minimise the consumption of HFC-23 in refrigeration, fire protection and other sectors through bans on the use of HFC-23 where alternatives exist
- develop an auditing framework for fluoropolymer production that would increase transparency and ensure HFC-23 destruction
- strengthen targeted monitoring of greenhouse gas emissions from fluorochemical production sites and regional monitoring in key regions
- relay concerns related to HFC-23 emissions from chemical pathways to produce PTFE and other fluoropolymers to the UN Environment Assembly's ad hoc open-ended working group on a science-policy panel to contribute further to the sound management of chemicals and waste and to prevent pollution.

The 35th Meeting of the Parties adopted Decision XXXV/7: Emissions of HFC-23. © IISD ENB Mike Muzurakis

Introduction

HFC-23, also known as trifluoromethane or fluoroform, is a chemical compound with the formula CHF_3. It is a synthetic hydrofluorocarbon (HFC) and a potent greenhouse gas with an atmospheric lifetime of 228 years and a global warming potential (GWP) of 14,700 over a 100-year period.[2]

While some direct uses for HFC-23 exist, it is primarily an unwanted by-product of HCFC-22 (chlorodifluoromethane) production. HCFC-22 itself is an ozone-depleting substance (ODS) which is being phased out under the Montreal Protocol.

For decades, HFC-23 emissions have been recognised as a 'low-hanging fruit' of climate mitigation, given that reduction of the amount of by-product generated as well as capture and destruction of the by-product are technically and economically feasible. But despite attempts to control emissions through international, regional and national policy measures, global HFC-23 emissions have steadily risen since the early 1990s.

From 2018-19, atmospheric concentrations of HFC-23 increased at a rate of 1.3 parts per trillion (ppt) per year, the fastest growth ever recorded. Emissions reached a high of approximately 17,300 ± 800 tonnes (t) in 2019, equivalent to 254 million tonnes of carbon dioxide ($MtCO_2e$), making HFC-23 the third largest contributor (20 per cent) to GWP-weighted emissions from all HFCs.[3]

The continuing high levels of HFC-23 emissions detected are not only contrary to the provisions of the Kigali Amendment, but they also significantly exceed the HFC-23 emissions that would be expected from reported emissions data.

This has prompted two decisions by the Montreal Protocol aimed at further understanding sources of the emissions as well as best practices to control them.

Updated reports from the Technology and Economic Assessment Panel (TEAP) and the Scientific Assessment Panel (SAP) for the 36th Meeting of the Parties taking place in Bangkok in October 2024 provide further information but have not yet been able to reconcile the significant levels of HFC-23 emissions being detected with emissions occurring from known sources.

History of HFC-23 abatement efforts

HFC-23 by-product is generated from HCFC-22 production, typically with a 1-3 per cent waste generation ratio by weight (known as 'w rate' i.e. 10–30 kg of HFC-23 by-product generated per tonne of HCFC-22), although this can be as high as four per cent. The amount of HFC-23 generated can be reduced through plant design and process optimisation, but not eliminated. Remaining HFC-23 can be destroyed with more than 99 per cent efficiency through thermal oxidation as an end-of-pipe process.[4]

Like other ODS, production and use of HCFC-22 is controlled by the Montreal Protocol. HCFC-22 is being phased out for emissive uses, with the phase-out already complete in non-Article 5 (non-A5, developed) countries and scheduled for 2030 in Article 5 (A5, developing) countries.

However, the production and use of HCFC-22 has continued to grow, due to its use as a feedstock which is exempt from the Protocol's control schedules. Almost 1.2 million tonnes of HCFC-22 was produced in 2022, most of it for feedstock use, in particular for the production of polytetrafluoroethylene (PTFE), a fluoropolymer with numerous applications, the best known being the non-stick coating on cooking pans (Teflon).[5] HCFC-22 is also used as a feedstock in the production of commonly used HFCs and HFOs.

A litany of failed HFC-23 control efforts

In 2006, the United Nations Framework Convention on Climate Change (UNFCCC) launched the Clean Development Mechanism (CDM), which allowed developing countries to earn saleable certified emission reduction (CER) credits from greenhouse gas emission reduction or removal projects.

Each CER credit was equivalent to one tonne of CO_2 and could be used to meet Kyoto Protocol targets.[6] The first projects registered under the CDM focused on abatement (i.e., capture and destruction) of HFC-23 emissions.

The 19 projects registered (11 in China, five in India and one each in Argentina, Mexico and the Republic of Korea) quickly dominated the CDM in terms of number of credits issued due to the very high GWP of HFC-23.

By 2010, HFC-23 destruction projects represented just 2.5 per cent of the CDM projects that had issued CERs, but these HFC-23 projects accounted for 214 million of the 407 million CERs issued (52.6 per cent).[7]

In 2007, HFC-23 projects came under increasing scrutiny after a Nature Commentary by Standford Law Professor Michael Wara revealed that HFC-23 credits would be worth €4.7 billion by 2012 (the end of the first compliance period), despite the estimated cost of destruction being just €100 million.

HFC-23 emitters were earning almost twice as much from CDM credits as they were from selling the HCFC-22 they produced.[8] In a subsequent working paper, Wara and his colleague David Victor described the projects as "a startlingly inefficient means for achieving emissions reductions in the developing world", noting that: "... refrigerant manufacturers were transformed overnight by the CDM into ventures that generated large volumes of CERs, with a sideline in the manufacture of industrial gases."[9]

The DuPont chemical company had also warned the CDM Methodology Panel in 2004 that the IPCC default waste rate of four per cent (i.e. generation of 0.04 tonnes of HFC-23 by-product per tonne of HCFC-22 produced) was too high and would discourage "efforts to minimise the amount of HFC-23 produced in the first place". As evidence, DuPont stated that its US facility had achieved a sustained waste generation of 0.01374 tonnes of HFC-23 produced per tonne of HCFC-22 manufactured.[10]

Given the exorbitant profits available, it was hardly surprising when an analysis of project monitoring reports revealed significant gaming of the system by the chemical companies to maximise HFC-23 emissions and thus the number of valuable carbon credits that could be gained through destruction of HFC-23.

A March 2010 request to revise the CDM's HFC-23 methodology revealed several ways in which CDM companies were inflating the CERs they could receive:[11]

- for many plants, the amount of HCFC-22 production and HFC-23 generation corresponded to the exact amounts that were eligible for carbon crediting, in some cases this being higher than years prior to the CDM
- two plants produced lower rates of HFC-23 by-product during periods where no carbon credits could be claimed and then increased the w rate once carbon credits could again be obtained
- one plant even stopped HCFC-22 production when it was not allowed to generate further credits and resumed operation when it became eligible for CERs.

Thus the carbon credits had incentivised additional HFC-23 generation and HCFC-22 production, itself a powerful greenhouse gas as well as an ODS.

In a subsequent investigation, the CDM Methodology Panel confirmed the specific concerns raised in the revision request, identifying a "series of circumstances under which the current methodology and its treatment of parameters HFC-23 waste ratio w, HCFC-22 production and lifetime may overestimate baseline emissions compared to the situation without the CDM."[12]

In November 2011, the methodology was revised, with the allowable HFC-23 waste ratio being cut from three to one per cent. Months earlier, the largest market for HFC-23 credits, the European Union (EU), had already recognised that changes to the methodology would not fix its inherent flaws.[13]

In January 2011, the EU voted to ban the use of HFC-23 and other industrial gas offset credits from April 2013 so they would no longer be eligible for use under the EU Emissions Trading Scheme.[14]

Today, HFC-23 destruction credits still represent more than one-fifth of all CDM CERs issued; almost 541 million HFC-23 CERs have been issued, compared to the total of 2.43 billion from all projects as of 5 September 2024 – some 22.2 per cent of the total.[15]

As a further example of the significant pitfalls in implementing market-based solutions in environmental policy, a similar situation occurred with HFC-23 projects under the Joint Implementation (JI) scheme, another Kyoto Protocol offsetting mechanism with projects in industrialised countries.

Windfall profits for HCFC manufacturers

With average CER prices in the early years of the CDM projects at around €12, substantial profits were made by manufacturers in India, China and elsewhere. For example, Gujarat Fluorochemicals Ltd (GFL), India's largest HCFC-22 producer, reported CER revenues of approximately $187 million in the financial year 2012 alone, compared to revenues of just $15.5 million from refrigerant sales.

According to company reports, cumulative revenue from CERs received by GFL between 2006-13 was 346,653 INR lacs, worth more than $750 million based on historical exchange rates.[18]

GFL used its CDM profits to establish an integrated chemicals complex at Dahej, Gujarat, where it set up India's largest manufacturing facility of PTFE. Part of the Dahej complex was a new 40,000 tonne HCFC plant.[19]

Similarly, HFC-23 destruction at Quimobásicos, a joint operation owned by Mexico's CYDSA and US chemical giant Honeywell, earned an estimated $136.2 million from the sale of CERs from 2006-11, accounting for 21 per cent of CYDSA's net revenues in 2011.[20]

In addition to manufacturers, the Chinese Government also earned significant revenues from HFC-23 destruction under the CDM, imposing a tax on CER revenues at a rate of 65 per cent. By December 2012, the Chinese Government had earned an estimated 12.15 billion RMB ($1.98 billion at the time) from its CER revenue tax, with the vast bulk coming from HFC-23 projects.[21]

A *Nature* study published in 2015 found that two Russian HFC-23 projects ramped up the waste gas generation far beyond previously reported levels in 2011 after caps on the amount of waste gas that could be credited were removed.[16] Data from Russian plants shows that co-production ratios in the order of one per cent were achieved before the introduction of the JI projects, at which point they were increased, in one facility to greater than four per cent.[17]

Post-CDM measures to address HFC-23 emissions

After the EU banned HFC-23 offsets, carbon markets in New Zealand, Australia, Canada and California quickly followed and the price of the CERs plummeted. In response, many of the companies that had operated HFC-23 destruction at their facilities under the CDM threatened to discontinue the practice and instead vent the HFC-23, despite the windfall profits already gained.[22]

In 2013, the Executive Committee of the Multilateral Fund (MLF) of the Montreal Protocol agreed on funding of $385 million to China for the first stage of its HCFC production phase-out (HPPMP). As part of the deal, China agreed that it "will coordinate with stakeholders and make best efforts to manage HCFC production and associated by-product production in HCFC plants in accordance with best practices to minimize associated climate impacts."[23] This resulted in the construction of 13 new destruction facilities at 15 HCFC-22 production lines that had not been covered by the CDM.[24]

EU legislation since 2014 has required producers to "take all necessary precautions to limit emissions of fluorinated greenhouse gases to the greatest extent possible" during production, transport and storage.[25] The EU legislation also requires that any HFC-23 by-product associated with HFCs, including during the manufacture of feedstocks for their production, has been destroyed or recovered in order for the HFCs to be placed on the EU market.[26]

In practice, this measure has been difficult to enforce but the revised 2024 EU F-Gas Regulation strengthens the enforcement of the measure by requiring producers and importers to draw up a declaration of conformity, including the provision of appropriate documentation.[27]

Ultimately, the adoption of the Kigali Amendment in 2016 mandated that all HFC-23 by-product emissions from HCFC (Annex C) or HFC (Annex F) production facilities should be destroyed to the extent practicable and using approved technologies from 1 January 2020 onward.[28]

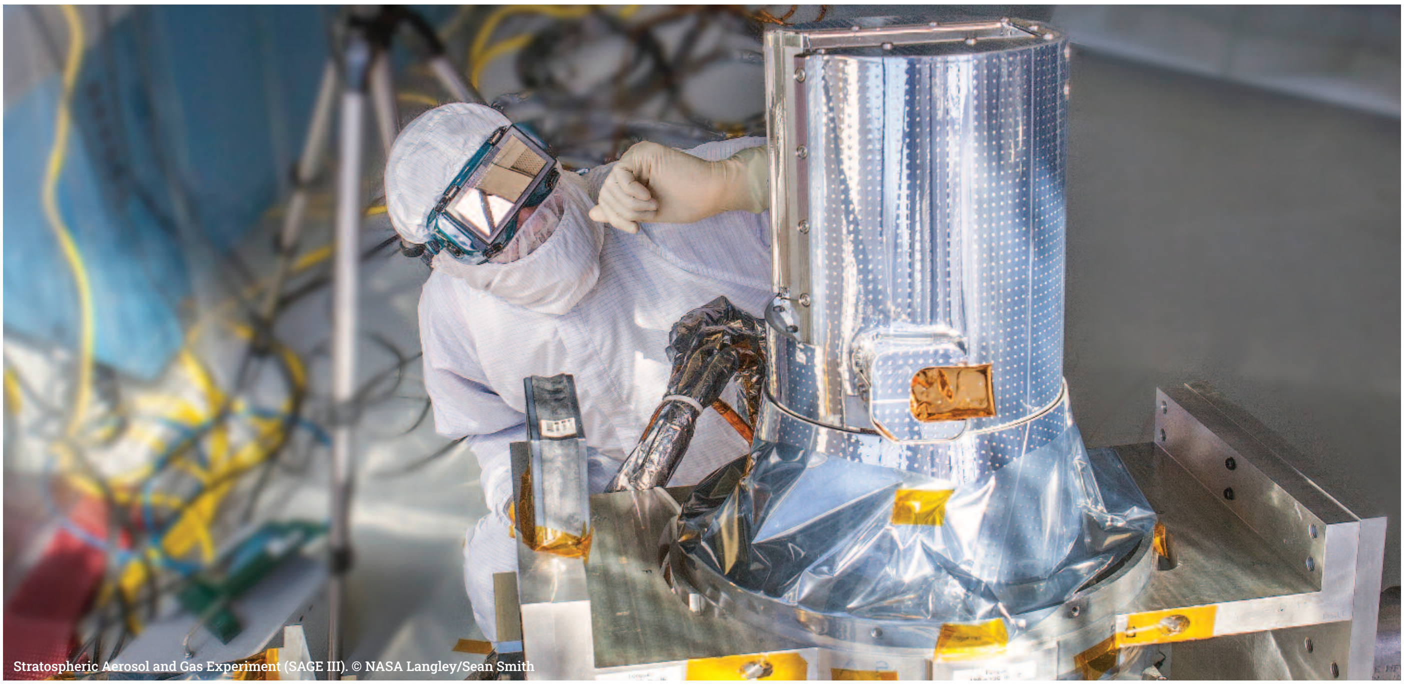
India announced comprehensive domestic measures to deal with HFC-23 by-product destruction in October 2016, to take place with immediate effect.[29] In 2021, upon ratification of the Kigali Amendment, China issued a Notice requiring that from 15 September 2021, HFC-23 produced as a by-product during the production of HCFC-22 or HFCs shall not be directly discharged.[30]

In 2021, the Executive Committee of the MLF approved funding of $3,833,384 and $2,262,630 to Mexico and Argentina to address HFC-23 emissions in their Quimobásicos and Fiasa HCFC-22 production facilities respectively. The MLF agreement commits the countries to ensure by 2022 that emissions from the lines are at or below 0.1 kg of HFC-23 emissions per 100 kg of HCFC-22.[31]

US ratification of the Kigali Amendment in 2022 led the US Environmental Protection Agency (EPA) to establish requirements for all entities producing HFC-23 to control these emissions no later than 1 October 2022, such that no more than 0.1 per cent of HFC-23 created on a facility line may be emitted (including any HFC-23 emissions during transportation to and destruction at a different facility), as compared to the amount of chemical intentionally produced on the line.[32]

Although Chemours had committed in 2015 to "control and, to the extent feasible, eliminate by-product emissions of HFC-23 at all its fluorochemical production facilities worldwide", the company's Louisville production facility continued to be by far the largest emitter of HFC-23 in the US (180 tonnes in 2021) and required a six-month extension to comply with the new EPA regulation.[33]

As of 2024, all HCFC-22 producing countries have ratified the Kigali Amendment.[34]



Stratospheric Aerosol and Gas Experiment (SAGE III). © NASA Langley/Sean Smith

Understanding HFC-23 emissions

In 2020, a Nature Communications article reported that HFC-23 emissions reached an "all-time high" of 15,900 tonnes/yr in 2018, despite reported emissions and pledged reductions from China and India which, they estimated, should have meant emissions in the region of just 2,400 tonnes/yr.[35]

The new reports from TEAP and SAP in response to Decision XXXV/7 further interrogate and update HFC-23 emissions, but fail to fully explain the gap between top-down and bottom-up emissions estimates.

HFC-23 emission levels according to atmospheric studies

Global atmospheric monitoring data shows a clear and substantial increase in the atmospheric abundance of HFC-23 over recent decades.[36]

In 1960, atmospheric levels of HFC-23 were approximately zero, as emissions from anthropogenic activity were not yet significant.[37] By 2022, atmospheric HFC-23 concentrations reached ~36 ppt.[38] HFC-23 has a long lifetime and high GWP value compared to other HFCs and thus the increase in atmospheric levels of HFC-23 has a relatively large warming effect. In 2020, atmospheric HFC-23 led to ~6.6 mW/m^2 of radiative forcing, 15 per cent of the total from all HFCs.[39]

Models of atmospheric processes can be used in combination with data from atmospheric monitoring to infer HFC-23 emissions. Although the amount of HFC-23 in the atmosphere has continuously increased since measurements began, the rate of increase has varied over the years due to fluctuations in the annual global emissions.

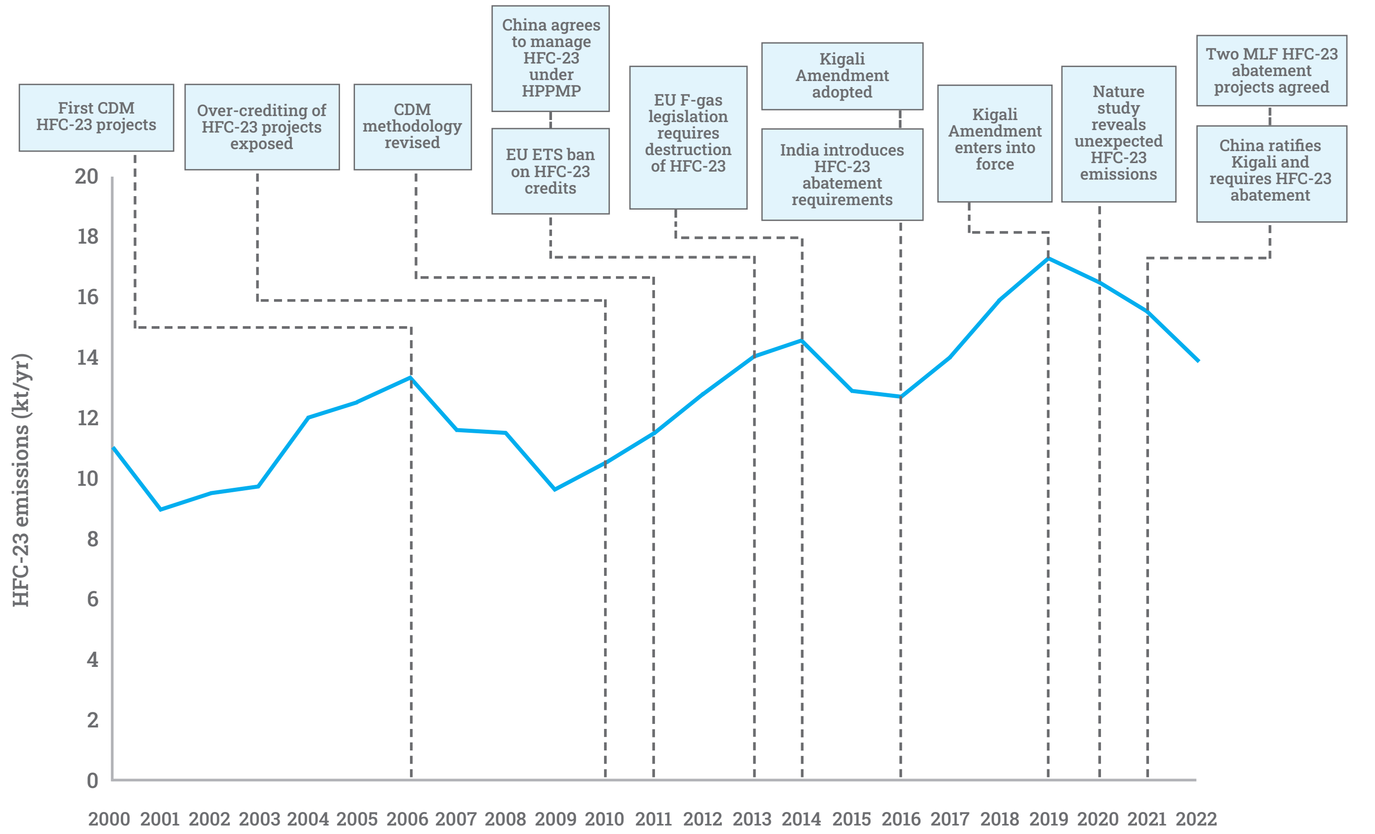
Until 2006, the growth rate of atmospheric HFC-23 concentrations generally increased, as did the inferred annual global emissions.[40] Between 2006-09, during the CDM period, the atmospheric concentration of HFC-23 increased at a slower rate, as emissions fell from 14,300 to 9,600 tonnes/yr.[41]

After 2009, HFC-23 emissions once again increased,[42] with the exception of a short period of decline between 2015-16, which may be explained by a reduction in global HCFC-22 production.[43]

The rate of growth of atmospheric HFC-23 also increased, reaching a maximum of 1.3 ppt/yr between 2018-19.[44]
In 2019, global emissions of HFC-23 were ~17,300 tonnes/yr, the highest level ever recorded.[45]

The amount of HFC-23 in the atmosphere has continued to increase since 2019, but the rate of increase has slowed and studies now show a fall in annual global emissions.[46] In 2022 global emissions of HFC-23 were ~13,900 tonnes/yr, roughly 20 per cent lower than the peak emissions recorded in 2019.[47]

Figure 1: Global emissions of HFC-23 with timeline of efforts to control them.



Sources: HFC-23 emissions from Stanley *et al.*, (2020), SAP (2024) and WMO (2022). For years where inferred HFC-23 emissions were not stated, HFC-23 emissions were estimated from graphs in these sources.

The HFC-23 gap

Until 2014, estimates of HFC-23 emissions derived via atmospheric monitoring (i.e., top-down estimates) were in good agreement with inventory based (i.e., bottom-up) estimates.[48] However, from 2015 onwards, a considerable gap developed, with emissions inferred from atmospheric monitoring far exceeding those explained by reported inventories.[49] In 2016, atmospheric monitoring data was used to infer global HFC-23 emissions of 12,700 tonnes/yr, but the bottom-up estimate was ~9,000 tonnes below this.[50]

In 2019, the discrepancy between top-down and bottom-up HFC-23 emissions estimates reached 15,000 tonnes (~220 $MtCO_2e$), meaning more than 85 per cent of emissions were not accounted for.[51]

In response to Decision XXXV/7: emissions of HFC-23, the SAP provided an update on HFC-23 emissions and atmospheric monitoring in September 2024.[52] Based on atmospheric monitoring data, it inferred global HFC-23 emissions of ~13,900 ± 700 tonnes/yr in 2022.[53] By comparing this figure to their assessment of expected emissions, the SAP concluded that the gap between measured and reported HFC-23 emissions was approximately 10,500–12,500 tonnes in 2022.

Regional scale atmospheric monitoring is invaluable to further understanding the sources of HFC-23 emissions. Of particular importance are new regional-scale monitoring studies which have shed light on HFC-23 emissions from China.[54] Although these studies cannot indicate China's total annual emissions of HFC-23, they demonstrate continuing, substantial HFC-23 emissions.[55]

Park *et al.* inferred emissions of ~5,000 tonnes/yr from eastern China alone in 2008.[56] This increased to ~9,500 tonnes/yr in 2019, following a temporary decrease in emissions during the CDM period and in 2015.[57] More recent studies from Huang *et al.* and Yi *et al.* suggest high levels of HFC-23 emissions from both eastern and northern China between 2020-23.[58] Park *et al.* found that there was good correlation between the spatial distribution of HFC-23 emissions sources and the location of known HCFC-22 facilities in eastern China and a subsequent study has indicated a possible link between some HFC-23 emissions and PTFE production sites.[59]

The regional emissions inferred in each of these studies far exceeds the total annual HFC-23 emissions reported by China or the bottom-up estimates of China's emissions based on abatement reported under the HPPMP.[60]

In its response to Decision XXXV/7: emissions of HFC-23, the SAP estimated that, based on the available data, between 2015-22 unreported emissions from China accounted for about 20-50 per cent of the global HFC-23 emissions gap.[61]

In light of this, it is of even greater importance that China provides full access to its domestic monitoring data, which improved extensively in recent years but has not yet been shared with the wider global scientific community.

Regional scale emissions data available for several countries other than China also showed emissions above those reported, but the additional emissions were small and do not explain a significant proportion of the emissions gap.[62]

However, regional scale data is not yet available for all parts of the world and is lacking for India, Russia and the US, three countries that account for a significant proportion of reported global HCFC-22 production.[63]

HFC-23 emission levels according to bottom-up estimates

Based on atmospheric monitoring data, SAP inferred global HFC-23 emissions of 13,900 ± 700 tonnes in 2022. In contrast, TEAP's best estimate in recent years (2020-24), based on reported and best available annual estimates of known emission sources, is 1,470-3,540 tonnes (see Table 1 and Figure 2).[64] This indicates unexplained emissions of between 9,560-13,230 tonnes.

TEAP attributes most of the gap to unknowns and uncertainties in Article 7 reporting of HFC-23 emissions, including how HCFC-22 production facilities are measuring and reporting HFC-23 emissions.

Although TEAP acknowledges unknowns and uncertainties in emissions from sources other than HCFC-22 production, it appears to be confident that all major sources of HFC-23 emissions have been identified and that "any smaller unknown sources are unlikely to bridge the large difference with SAP estimates".

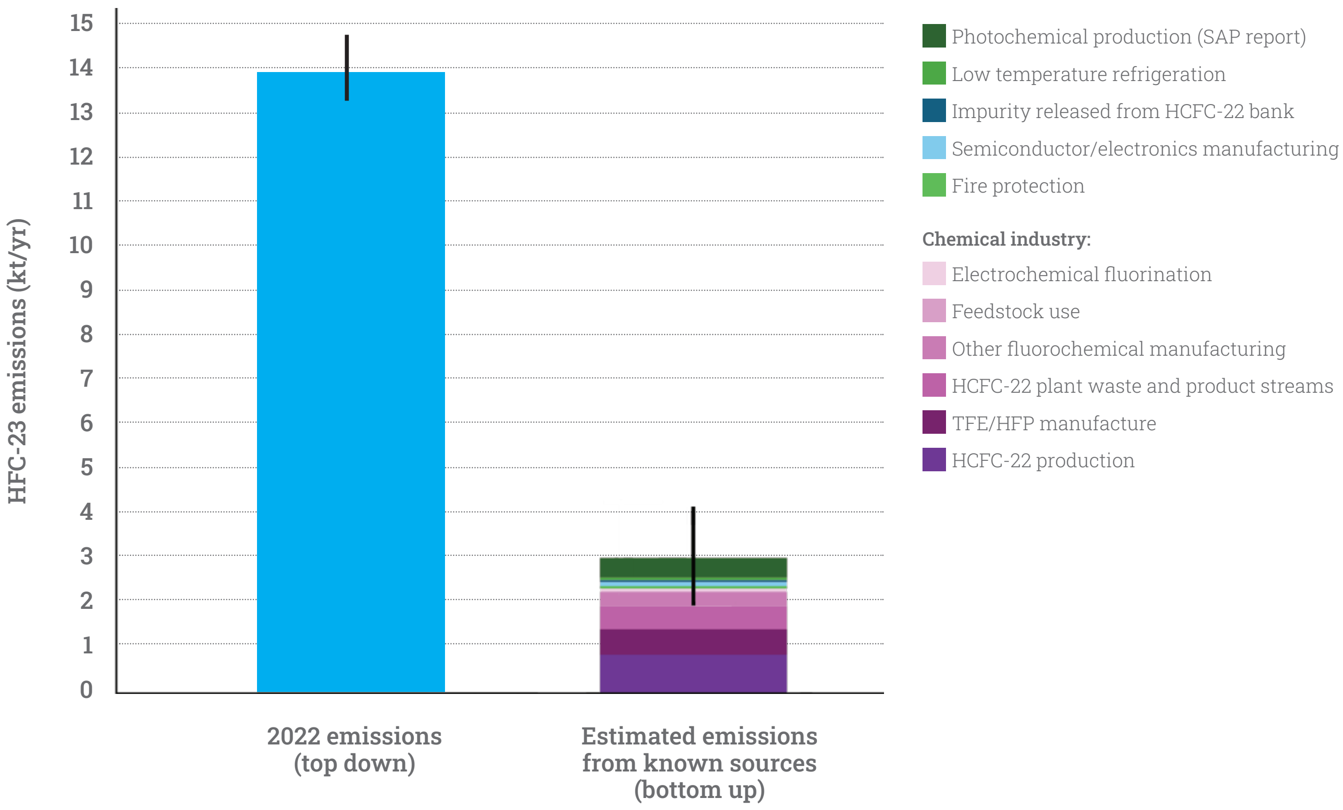
TEAP's bottom-up estimate is based on a compilation of reported and available best estimates of HFC-23 emissions from known emission sources. These are discussed, with commentary on the quality of the data available.

Table 1: Annual reported and available best estimates of HFC-23 emissions from known emission sources (tonnes).

Sources of HFC-23 (for the year with available data to make estimates)	Estimated HFC-23 emissions (tonnes)
Reported HFC-23 emissions under Article 7 and UNFCCC (for the US)	
HCFC-22 production (2022)	~836
Estimated HFC-23 emissions	
TFE/HFP manufacture (estimated, 2023)	100-1,000
HCFC-22 plant waste and product streams (estimated, 2023)	100-1,000
Other fluorochemical manufacturing (estimated, 2024)	<300
Semiconductor/electronics manufacturing (WSC data, 2020)	92
Fire protection (estimated, 2022)	50
Impurity released from HCFC-22 bank (estimated, 2020)	40
Feedstock use (estimated based on A7 reported consumption data, 2022)	22
Electrochemical fluorination (estimated, 2020)	10-100
Low temperature refrigeration (estimated, 2020)	10-100
Total reported and estimated HFC-23 emissions from known sources	**1,470-3,540**

Source: Table 4.1 in TEAP (2024) Response to Decision XXXV/7: Emissions of HFC-23.

Figure 2: Top down estimates of HFC-23 emissions compared to total reported and estimated emissions from known sources.



Source: Top down HFC-23 emissions inferred from atmospheric monitoring SAP (2024). Estimated emissions from known sources and the reported and best available estimates (TEAP 2024), combined with estimated emissions due to photo-chemical production of HFC-23 in the atmosphere, as reported in SAP (2024).
Error bars indicate the range of values or uncertainty in the best estimates or inferred values.

Reported HFC-23 emissions data

Based on IPCC default w rates (1.5-3.0 per cent), the expected generation of HFC-23 from HCFC-22 is in the range of 18,000-36,000 tonnes in 2022.[65]

TEAP presents reported emissions of HFC-23 in 2022 from the production of Annex C Group 1 and Annex F substances of about 836 tonnes, as reported under Article 7 of the Montreal Protocol (695 tonnes), plus, for the US only, data contained in common reporting format (CRF) tables submitted by Annex 1 Parties under UNFCCC reporting guidelines (140 tonnes).[66]

TEAP notes that "it appears that most, if not all, the reported amounts relate to HFC-23 emissions from HCFC-22 production", but the reality is not clear. The total non-A5 and A5 reported HFC-23 emissions to the Montreal Protocol are actually lower than data from just six Annex 1 countries reported to the UNFCCC (see Table 2). This is primarily due to a significant difference in reporting from the Russian Federation, which reports more than 1,000 tonnes of emissions each year to the UNFCCC while reporting zero emissions to the Montreal Protocol. Belgium and the Russian Federation also report 'fugitive emissions from fluorochemical production' which are not reported to the Montreal Protocol. These reporting discrepancies are not discussed in the TEAP report.

EIA notes that Venezuela and the Republic of Korea, which ratified the Kigali Amendment in December 2022 and January 2023 respectively, have HCFC-22 production facilities and would therefore be expected to generate and possibly emit HFC-23. According to reports submitted to the MLF Secretariat, the HCFC-22 production facility in the Republic of Korea stopped operating its HFC-23 incineration facility in November 2012.[67]

Expected global HFC-23 by-product generation from other HCFCs and HFCs

Several chemical mechanisms can generate HFC-23 as a by-product. It is primarily (95 per cent) generated by the fluorination of chloroform to HCFC-22 pathway, but it can also be generated in chemical pathways used to produce other HCFCs and HFCs, and other substances, with the by-product generation rate dependent on the processes. While there is significant uncertainty and an almost total lack of data on which to base estimates, TEAP lists seven

Table 2: HFC-23 emissions reported under Article 7 of the Montreal Protocol[68] and HFC-23 by-product emissions from HCFC-22 production reported to UNFCCC (tonnes).[69]

	2019		2020		2021		2022
	Article 7 reporting of HFC-23 emissions (number of facilities)	UNFCCC reporting of HFC-23 by-product emissions	Article 7 reporting of HFC-23 emissions (number of facilities)	UNFCCC reporting of HFC-23 by-product emissions	Article 7 reporting of HFC-23 emissions (number of facilities)	UNFCCC reporting of HFC-23 by-product emissions	Article 7 reporting of HFC-23 emissions (number of facilities)
European Union	22.93 (3)	23.01	9.92 (3)	9.99	17.73 (3)	17.81	0.82 (4)
France	4.50 (1)	4.50	3.35 (1)	3.36	0.34 (1)	0.34	0.27 (1)
Germany	0.00 (1)	IE	0.00 (1)	IE	0.00 (1)	IE	0.00 (1)
Italy	-	0.08	-	0.06	-	0.07	0.55 (1)
Netherlands (Kingdom of the)	18.43 (1)	18.43	6.57 (1)	6.57	17.39 (1)	17.40	0.00 (1)
Russian Federation	-	1,058.15	-	1,174.16	0.00 (2)	1,105.14	0.00 (2)
Japan	0.00 (3)	0.90	9.31 (3)	9.50	8.64 (3)	8.90	0.03 (3)
USA		250.88		141.96		180.26	
Total non-A5 reported emissions	**22.93**	**1,332.94**	**19.23**	**1,335.60**	**26.38**	**1,312.11**	**0.85**
Mexico	111.89 (1)		39.28 (1)		128.52 (1)		31.89 (1)
Argentina	-		36.17 (1)		33.31 (1)		17.31 (1)
China	-		48.10 (19)		1,089.95 (20)		637.39 (21)
Democratic People's Republic of Korea	9.1 (1)		9.10 (1)		8.40 (1)		8.38 (1)
India	-		-		0.00 (4)		0.00(4)
Total A5 reported emissions (Article 7 data only)	**120.99**		**132.65**		**1,260.18**		**694.97**
Total Non-A5 and A5 reported HFC-23 emissions, Article 7	**143.92**		**151.88**		**1,286.56**		**695.82**

potential HFC production pathways (HFC-32, HFC-125, HFC-134a, HFC-152a, HFC-143a, HFC-227ea and HFC-245fa) that could generate HFC-23 by-product and one other chemical pathway for producing HCFC-142b, estimating that these generate approximately one per cent of total HFC-23 by-product generation.[70]

Highly concerning is the statement from TEAP that "Publicly available data for this HFC-23 generation and/or emission is extremely limited and even the exact quantity of each fluorocarbon produced per year is uncertain, so any methodology used to estimate the associated annual HFC-23 emission from these processes has a very high degree of uncertainty."

TEAP estimates that 3-4 per cent of global HFC-23 by-product is generated from production of non-Annex F or Annex C substances, primarily the pyrolysis of HCFC-22 to make tetrafluoroethylene (TFE) and hexafluoropropylene (HFP), which are used to make fluoropolymers, e.g. PTFE as well as other HFCs and HFOs.

TEAP understands that this process generates up to 1kg of HFC-23 per tonne of HCFC-22 consumed, a 0.1 per cent w rate. This is a concern given that the global market for PTFE has grown significantly in recent years, is projected to experience significant growth (CAGR 3.5 per cent) this decade and is not monitored by the Montreal Protocol.[71] TEAP estimates that 97 per cent of HCFC-22 feedstock is used to produce TFE and HFP. Other non-Annex F or Annex C pathways include those used to produce CFC-113 and CFC-114, from perchloroethylene.[72]

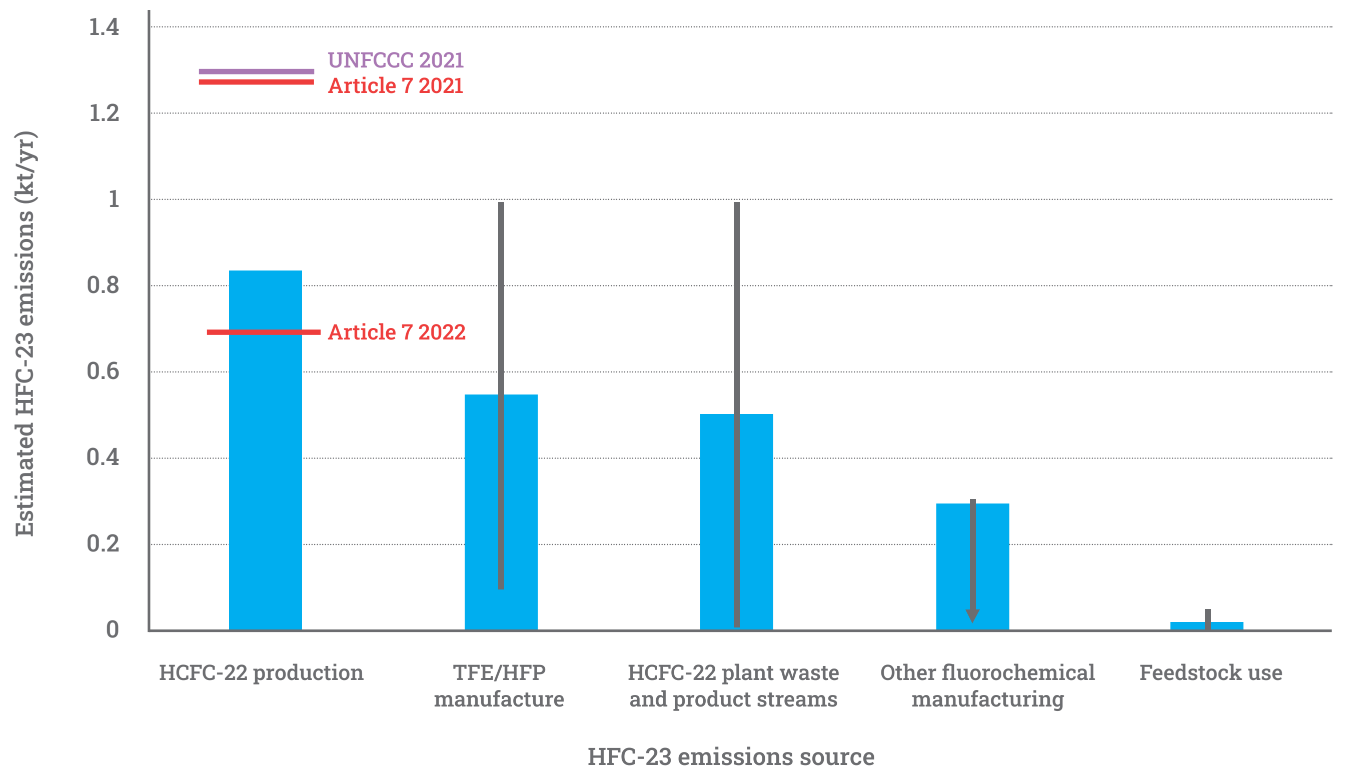
What is "to the extent practicable" in HFC-23 abatement?

Given a lack of reliable reporting, it is still unclear what would be the 'natural' HFC-23 waste generation rates from HCFC-22 production in facilities operating primarily to maximise efficiency and profitability and what is the maximum potential abatement of HFC-23.

The ratio of observed global HFC-23 emissions relative to reported HCFC-22 production (E23/P22) can give an indication of the extent to which by-product emissions are being captured and destroyed, although it will to some extent be biased by emissions from other production processes.

The E23/P22 value increased between 2010-19, indicating a decrease in the effective abatement of by-product emissions. By 2020, the average E23/P22 had decreased from 1.74 per cent to ~1.16 per cent and although this implies abatement levels have increased, it is still far above the emissions factor believed practicable or required under the MLF (0.1 per cent).[73]

Figure 3: Uncertainties and error margins around estimated HFC-23 emissions from chemical industry sources according to the best estimates from TEAP. Emissions reported under Article 7 (EU, Japan, Mexico, Russian Federation, India, Democratic People's Republic of Korea, China, and Argentina) and UNFCCC (non-A5 countries only) are marked for comparison.



Sources: TEAP (2024), Article 7 data and UNFCCC Common Reporting Format Tables.

Further insight can be gained by a recent study published in Nature, which applied a new method to achieve facility level atmospheric monitoring of emissions from the Chemours plant in Dordrecht, the Netherlands.[74]

Prior to this study taking place, Chemours had implemented measures to reduce F-gas emissions at the facility, including abatement through the thermal destruction of waste gases.[75] Atmospheric measurements were conducted over a seven-week period in 2022 and emissions of several substances controlled under the Montreal Protocol, including HCFC-22, HFC-23 and PFC-318, were detected. The results were considered representative under regular operation conditions and hence emissions were extrapolated and inferred on an annual basis.

The study inferred annual emissions of HFC-23 and HCFC-22 which exceeded the total annual emissions reported by Chemours to the Government of the Netherlands in 2021 or 2022 (see Table 3). Furthermore, although any interruption or failure of the abatement processes would cause a spike in emissions, and despite several such instances occurring during the monitoring period, these 'failure periods' were excluded from the quantification of emissions conducted in this research. If this study had been able to factor in the additional emissions occurring during these failure periods, the inferred emissions would likely be even greater.

The emission factor for HFC-23 of 0.19 (0.13-0.24) per cent inferred through the study is significantly lower than would be expected absent abatement, and well below the global average E23/P22 value. However, it still exceeded both the level considered practicable by the SAP (0.08 per cent) and the level required from HFC-23 destruction projects funded under the MLF (0.1 per cent), both of which already consider abatement failure periods.[76]

This is all the more surprising since Chemours, before it was spun off from DuPont, claimed as far back as 2004 to have achieved a sustained 1.37 per cent HFC-23 generation rate; therefore, with thermal oxidation, one would expect a lower emissions factor.

It should be noted, however, that this research quantified emissions from the whole facility, not just the production of HCFC-22 as is assumed in the SAP and MLF emission factors. As such, the results may indicate that the abatement process is operating below maximum efficiency or could imply that there are unabated emissions from elsewhere in the facility. The discrepancies between reported and inferred emissions – and the relatively high emissions factor established by the research – highlight both the need for stronger independent verification of emissions and

Table 3: Estimated emissions from Chemour's Dordrecht facility compared to reported data.

	Reported data (tonnes)		Inferred annual emissions (tonnes/yr)	Inferred emissions factor (E23/P22)
	2021	2022		
HFC-23	17.4	10.4	47 (36-55)	0.19 (0.13-0.24)%
HCFC-22	22.11 (total HCFCs)	18.66 (total HCFCs)	62 (44-76)	0.25 (0.16-0.32)%


The Chemours facility in Dordrecht, the Netherlands. © Paul Van de Velde

Sources: Rust *et al.* (2024)[77] and Government of the Netherlands Emission Registration data for Dutch Companies.[78]

abatement and the need to better address sources of fugitive emissions during manufacturing, in addition to those emitted from the stack.

Also requiring further consideration is the interruption or failure of abatement processes, for example during routine maintenance. According to the Government of India order on HFC-23 abatement, companies are required to keep their 'down time' below 10 per cent and to maintain sufficient storage capacity to ensure all HFC-23 is stored during any authorised shutdown and under no circumstances vented.[79]

Likewise, China's 2021 Circular on Controlling HFC-23 emissions specifies that companies must provide HFC-23 storage facilities or other measures to avoid emitting HFC-23 during shutdowns. Further, China states that if HFC-23 recovery, storage and destruction facilities are not operating, the HCFC-22 or HFC production processes must be stopped to avoid HFC-23 emissions.[80]

Emissions arising from HFC-23 use

HFC-23 is used in several sectors including fire protection, refrigeration, semiconductor and electronics manufacturing and as a feedstock in the production of other chemicals.

Consumption of HFC-23 in 2022, excluding feedstock use, as reported under Article 7, was 2,510.4 tonnes.[81] According to data reported to the MLF, 1,532 tonnes (61 per cent) of this consumption occurred in A5 Parties in the following sectors:

- firefighting – 3.9 tonnes
- refrigeration manufacturing – 6.6 tonnes
- refrigeration servicing – 62.8 tonnes
- solvents – 0.2 tonnes
- other – 1,464.1 tonnes (two countries reported under 'other', with one country confirming it is for refrigeration servicing; however the amount is not documented).[82]

TEAP bottom-up emissions attribute 152-242 tonnes of HFC-23 emission to consumption of HFC-23 in refrigeration, fire protection, solvent and semiconductor-related applications (see Table 4). Even at the high end of the range, this is an overall emission rate of less than 10 per cent.

EIA questions TEAP's estimated range of emissions of 10-100 tonnes for low-temperature refrigeration, given that emissions of 103 tonnes in 2021 were reported to the UNFCCC from just eight non-A5 Parties (not including Japan or US – see Table 5).[84]

In addition, data reported to the MLF suggests that more than half of reported HFC-23 consumption is in A5 Parties, primarily in the refrigeration servicing sector, which consumed a quantity almost 10 times higher than refrigeration manufacturing in 2021.

Table 4: Emissions from direct use of HFC-23 according to TEAP (2024).

Sources of HFC-23 (for the year with available data to make estimates)	Estimated HFC-23 emissions (tonnes)
Semiconductor/electronics manufacturing (WSC data, 2020)	92
Fire protection (estimated, 2022)	50
Low temperature refrigeration (estimated, 2020)	10-100
Estimated HFC-23 emissions from known consumption	**152-242**

Source: TEAP (2024)[83]

Table 5: HFC-23 emissions from its use as refrigerant in 2021, reported to UNFCCC.

2021	Emissions (tonnes)
Australia	53.582
Belarus	0.004
Canada	0.287
EU	21.065
Iceland	0.004
Norway	0.091
Russian Federation	27.675
Switzerland	0.301
Total	**103.009**


HFC-23 is used as an ultra-low temperature refrigerant, for example to freeze tuna at -60°C.

Source: UNFCCC Common Reporting Format Tables[85]

Other HFC-23 sources

In its report, TEAP estimates HFC-23 emissions from a range of 'other' sources, including from electrochemical fluorination (10-100 tonnes), from impurities in the HCFC-22 bank (40 tonnes) and from the use of HFC-23 for feedstock (22 tonnes).[86]

Recent scientific research also suggests photo-chemical production of HFC-23 can occur in the atmosphere from the ultraviolet (UV) photolysis of CF_3CHO (trifluoroacetaldehyde). Trifluoroacetaldehyde is produced during the atmospheric oxidation of several industrially important HFOs, which significantly increases their actual radiative effect over and above what is implied by their GWP.[87]

Source gases having a chemical structure that could lead to HFC-23 formation which are in the atmosphere in sufficient concentrations are HFC-143a, HFC-236fa, HFC-245fa, HFC-365mfc, HCFC-133a, HFO-1234ze, HFO-1336mzz and HCFO-1233zd. Based on these, the SAP estimates that up to 430 tonnes of HFC-23 emissions could be attributed to photo-chemical production in the atmosphere, although there are still uncertainties and further scientific research into the reactions involved is needed.[88]

Similarly, a new refrigerant blend called R-466A, which consists of 49 per cent HFC-32, 39.5 per cent CF_3I and 11.5 per cent HFC-125, has been designed by Honeywell as a non-flammable non-toxic lower-GWP replacement for HFC-410A in air-conditioning.[89]

However, the breakdown of CF_3I to produce HFC-23 within equipment was demonstrated 30 years ago and has even been observed directly in accelerated lifetime testing of R466A.[90]

Closing the emissions gap

It is clear from the updated TEAP and SAP reports that understanding HFC-23 emissions is highly complex. The challenge is compounded by the existence of multiple potential sources of HFC-23, the significant lack of data due to industry confidentiality and the plethora of monitoring and reporting problems, such as the under-reporting of emissions recently exposed in Europe.

In some instances, EIA believes that TEAP's bottom-up estimated emissions could be on the low side. However, even when emissions are added to reflect those Parties not currently reporting (such as Venezuela and the Republic of Korea), the greater quantities reported under the UNFCCC than the Montreal Protocol (as in the case of the Russian Federation) and the higher estimates for emissions from refrigeration, there is still a very significant gap.

Unlike the reported data, the atmospheric monitoring data is clear – emissions from China account for up to 50 per cent of the global HFC-23 emissions gap from 2015-22. This indicates that abatement practices at facilities in China have not been implemented to the extent reported.

An additional explanation which should be considered is the potential for illegal production of HCFC-22 in China, with concomitant HFC-23 emissions. Although the Parties to the Montreal Protocol do not consistently report cases of illegal production of controlled substances, there are several known cases of illegal HCFC-22 production in China over the past 10 years:

- in 2013, an enterprise transformed its HFC-32 facility to illegally produce HCFC-22 feedstock for its downstream TFE facility[91]
- in 2014, an enterprise set up an HCFC-22 production line to use it as feedstock in its downstream TFE and HFC-125 facility without approval[92]
- in June and August 2020, two HFC-32 producers in Hebi city and Jiaozuo city, Henan province, were found to have illegally produced HCFC-22 – more than 12 tonnes of HCFC-22 were confiscated at the sites.[93]

It would seem to be a safe assumption that any illegal production would not be undertaking efforts to either minimise generation of HFC-23 or destroy emissions, thus one could assume that the emission factor from such facilities would be at the higher end of known waste ratios.

While a focus on China is warranted, it must be acknowledged that the atmospheric monitoring assessment leaves at least 50 per cent of the emissions unaccounted for, while regional emissions are not available for other major HCFC-22 producing countries – India, the US and the Russian Federation.

A significant gap in current understanding is the extent of emissions from the production of fluoropolymers such as PTFE and from the rapidly increasing production of HFOs. In TEAP's 2023 report, it acknowledges that some chemical pathways and processes used to produce HFO-1234yf go through HCFC-22, HFP and/or TFE intermediates, generating HFC-23 emissions from the manufacture of HCFC-22 and the manufacture of TFE/HFP from HCFC-22.[94] It is not clear to what extent these emissions are being reported, if at all, given that HFOs and HFP/TFE are not Annex C or F controlled substances.

The situation brings into sharp relief the obvious need to improve monitoring, reporting and verification under the Montreal Protocol – a subject that has received inadequate attention from the Parties since the emergence of unexpected CFC-11 emissions in 2018.[95]


Chemour's fluorochemical facility in Dordrecht. © JStuij

Conclusions and recommendations

Cumulative HFC-23 emissions since the adoption of the Kigali Amendment in 2016 are almost 106,000 tonnes, equivalent to 1.56 billion tonnes of CO_2.[96]

Most of these emissions should not have occurred, given the multiple corporate and government commitments to abate HFC-23 emissions and the significant investment through the CDM into destruction technologies in most HCFC-22 producing facilities in developing countries.

The high level of global HFC-23 emissions is entirely inconsistent with reported data suggesting a substantial rise in abatement by major HCFC-22 producing countries.

The science shows that up to half of the problem emanates from China's fluorochemical industry; however, regional monitoring is lacking around other big producers, including the US, India and the Russian Federation.

It is a scandal that fluorochemical companies continue to hide behind commercial confidentiality and lax monitoring and reporting while pumping out dangerous greenhouse gases that exacerbate the climate crisis. That they are doing so despite the availability of technically feasible and economically viable abatement technologies, which have existed for more than 20 years, is even more egregious.

Although the HFC-23 emissions threaten compliance with the Kigali Amendment, not a single Party responded to Decision XXXV/7 to share available relevant scientific or technical information that could help inform the SAP and TEAP reports.

The significant discrepancies in data reporting, even between the Protocol's own institutions, and the lack of available data to fully understand current HFC-23 emissions lends further concrete backing to EIA's call for a comprehensive evaluation and strengthening of the Montreal Protocol's institutions and processes, including monitoring, reporting, verification and compliance.

The evidence also highlights the critical importance of ongoing discussions within the Protocol surrounding emissions of feedstocks and fluorochemical processes in general.

The Parties to the Montreal Protocol need to respond strongly to this worrying situation. As the next steps are considered at the 36th Meeting of the Parties (MoP36) to the Montreal Protocol in Bangkok, EIA calls on the Parties to consider the following recommendations:

- To request additional information from TEAP and SAP, using expert advice where necessary and involving the MLF Secretariat in order to:
  - resolve data reporting discrepancies, including data reported to the MLF through production sector verification reports, UNFCCC data and Article 7 data
  - resolve continued gaps in understanding due to the lack of transparency around fluorochemical production, including more comprehensive analysis and estimates of HFC-23 emissions through the production of PTFE, HFCs and HFOs, considering the benefits of establishing pilot projects under the MLF to provide additional information
  - elaborate on approaches used by Parties when measuring and reporting HFC-23 emissions and set guidance for Article 7 reporting and verification, including defining 'extent practicable' and ensuring it includes the use of storage to avoid emissions during shutdown.
- To take immediate steps to minimise the consumption of HFC-23 in refrigeration, fire protection and other sectors, through bans on the use of HFC-23 where alternatives exist
- As part of a comprehensive strengthening of monitoring, reporting and verification under the Montreal Protocol, to:
  - develop an auditing framework for fluoropolymer production that would increase transparency and ensure HFC-23 destruction
  - strengthen targeted monitoring of greenhouse gas emissions from fluorochemical production sites and regional monitoring in key regions.

Finally, EIA urges Parties to the Montreal Protocol to request the Ozone Secretariat to relay concerns related to HFC-23 emissions from chemical pathways to produce PTFE and other fluoropolymers to the UN Environment Assembly's ad hoc open-ended working group on a science-policy panel to contribute further to the sound management of chemicals and waste and to prevent pollution.

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