MONTREAL PROTOCOL ON SUBSTANCES THAT DEPLETE THE OZONE LAYER

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REPORT OF THE TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL

SEPTEMBER 2026

VOLUME 3

RESPONSE TO DECISION XXXVII/2: EMISSIONS OF HFC-23

UN environment programme

Montreal Protocol on Substances that Deplete the Ozone Layer

United Nations Environment Programme (UNEP)
Report of the Technology and Economic Assessment Panel

September 2026

VOLUME 3: RESPONSE TO DECISION XXXVII/2: EMISSIONS OF HFC-23

The text of this report is composed in Times New Roman.

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https://ozone.unep.org/science/assessment/teap

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ISBN: 978-9914-733-72-3

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Acknowledgements

The TEAP and its Technical Options Committees and members acknowledge with thanks the outstanding contributions from all the individuals and organisations that provided support to the Panel, Committees, and members. The opinions expressed are those of the Panel and the Committees and do not necessarily reflect the views of any sponsoring or supporting organisation.

Foreword

The September 2026 TEAP Report

The 2026 TEAP Report consists of 4 volumes:

Volume 1: TEAP 2026 Progress Report

Volume 2: TEAP May 2026: Assessment of the Funding Requirement for the Replenishment of the Multilateral Fund for the Period 2027-2029

Volume 3: TEAP September 2026: Response to Decision XXXVII/2: Emissions of HFC-23

Volume 4: TEAP September 2026: Supplement to the May 2026 TEAP Replenishment Task Force Report

This is Volume 3.

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Executive Summary

This report includes sections responding to each of the following paragraph and its sub-paragraphs of decision XXXVII/2, relating to emissions of HFC-23:

1. To request the Technology and Economic Assessment Panel and the Scientific Assessment Panel to provide an update on emissions of HFC-23 to the Thirty-Eighth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, taking into account the information submitted by parties in response to decision XXXVI/3 and pursuant to paragraph 2 below and including the following:
   (a) Additional analysis of the discrepancy between reported emissions and those derived from atmospheric measurements, including the methodologies applied;
   (b) A description of the information and data sources used, identifying any gaps or limitations;
   (c) Additional information on methodologies adopted by parties for estimating and reporting HFC-23 emissions as well as best practices for improvements to minimize such emissions;

The report includes additional contextual information on other HFC-23 generation and/or emissions, i.e., from chemical pathways used in the production of substances that are not Annex C, Group I substances (hydrochlorofluorocarbons or HCFCs), or Annex F substances (hydrofluorocarbons or HFCs), and from feedstock and consumptive uses. This additional contextual information was considered useful in understanding the relative importance of chemical pathways used in the production of Annex C, Group I, and Annex F substances that may generate HFC-23 as a by-product, which is the focus of this decision.

During the development of this report, TEAP coordinated with the SAP and has included information provided by the SAP from its 2026 Assessment on updated estimates of emissions of HFC-23 derived from atmospheric measurements.[1]

ES.1 Compilation of information on the amount of HFC-23 generation and emissions

In 2023, the TEAP response to the previous decision XXXIV/7, paragraph b, provided a compilation of information on the amount of HFC-23 generation and emissions from facilities that manufacture Annex C, Group I, or Annex F substances. It drew on several sources for this information, including United Nations Framework Convention on Climate Change (UNFCCC) submissions by Annex I countries; the Intergovernmental Panel on Climate Change (IPCC); Article 7 data reported under the Montreal Protocol; data reported to the Executive Committee of the Multilateral Fund (ExCom); and the Scientific Assessment Panel (SAP).

In 2024, in its response to decision XXXV/7, TEAP provided updated information on other HFC-23 consumptive and emissive uses, including as a by-product from the production of other Annex C, Group I substances (HCFCs) and Annex F substances (HFCs). In 2025, the 2024 report was updated in response to decision XXXVI/3.

In this 2026 report, responding to the present decision XXXVII/2, these data have been updated as follows:

- Data for both HFC-23 by-product generation (voluntarily) and for HFC-23 emissions (required) from the production of Annex C HCFCs and Annex F HFCs have been reported by

[1] World Meteorological Organization (WMO). *Scientific Assessment of Ozone Depletion: 2026, GAW Report No. xxx*, WMO: Geneva, 2026. (In preparation)

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parties under Article 7 to the Ozone Secretariat; quantities are reported as annual totals and emissions are available by individual party. These data are incomplete for 2019, 2020, 2021 and 2022 due to the timing of reporting obligations consequent upon when parties ratified the Kigali Amendment. However, the datasets for 2023 and 2024 are considered as complete.

- The consolidated data for *HFC-23 by-product generation* from HCFC and HFC production (without abatement) in 2023 was 24,376 tonnes and in 2024 was 23,809 tonnes.
- The consolidated data for *HFC-23 emissions* reported as by-product from HCFC-22 and from HFC production was 959 tonnes in 2023 and 1,003 tonnes in 2024.

TEAP estimates of annual HFC-23 emissions from additional other industrial and sector use sources are about 500 to 2,500 tonnes, including the following:

- Pyrolysis of HCFC-22 to produce TFE/HFP (~100–1,000 tonnes, based on estimated associated HFC-23 by-product generation without possible emissions abatement)
- Other fluorochemical manufacturing (e.g., hexafluoroacetone) (~70 tonnes)
- Feedstock use of HFC-23 (~26 tonnes)
- HFC-23 present as an impurity in other chemicals that are used in emissive uses (e.g., ~27 tonnes HFC-23 emissions arising from the HCFC-22 bank)

The combined total of reported HFC-23 emissions as a by-product from the production of Annex C, Group I substances (HCFCs) and Annex F substances (HFCs) for 2024 and the most recent available "bottom up" estimate of annual HFC-23 emissions from other known emissions sources is about 1,500–3,500 tonnes.[2]

These estimates exclude the potential additional source of HFC-23 from the atmospheric degradation of HFCs, HFOs, and HCFOs of less than around 200 tonnes per year in recent years, as reported by SAP.[3] That is, certain HFCs, HFOs, and HCFOs form trifluoroacetaldehyde (CF_3CHO) as a degradation product in the atmosphere. A certain fraction of this gas can photolyze to generate HFC-23. An additional lesser HFC-23 source comes from the direct ozonolysis of HFOs and HCFOs.

While global emissions derived from atmospheric monitoring peaked at 17,000 ± 1,000 tonnes per year in 2018 and 2019, they have since decreased and been relatively constant at 14,000 ± 1,000 tonnes per year in 2022, 2023, and 2024.[4]

This 2026 report continues to identify differences and uncertainties in estimates for global HFC-23 generation and emissions based on currently available data.

SAP has described the uncertainties in the derivation of "top-down" emissions estimates based on atmospheric observations. However, these uncertainties do not bridge the differences between the "top-down" and "bottom-up" estimates.

TEAP has further reviewed the unknowns and uncertainties of its "bottom-up" estimations for HFC-23 emission sources other than from production of HCFC-22, other Annex C, Group 1, and Annex F controlled substances, as requested under decision XXXVII/2. The current review by TEAP continues

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[2] Rounded from 1,526–3,526 tonnes. These are contemporaneous annual estimates for the recent years for which data is available or estimated, which is from 2020-2024.

[3] World Meteorological Organization (WMO). *Scientific Assessment of Ozone Depletion: 2026, GAW Report No. xxx*, WMO: Geneva, 2026. (In preparation).

[4] Ibid.

to conclude that inaccuracies in estimations of these emissions would be relatively small and are unlikely to bridge the difference with atmospheric-derived emissions estimates.

TEAP has identified the major known industrial and use-related sources for which information is currently available. No additional known sources identified through this review appear capable individually or collectively, on available evidence, of bridging the difference.

The difference, of the order of 10,000 tonnes, between the SAP's "top-down" and the TEAP's "bottom-up" estimates of global emissions of HFC-23 cannot currently be explained. Given this large difference, a question arises about the completeness of the data reported under Article 7 and whether it includes all sources of HFC-23 emissions.

ES.2 Best practices available to measure, estimate, report and verify HFC-23 by-product emissions

In response to decision XXXVI/3, paragraph 6, the 2025 TEAP report provided a summary of information on current methodologies to estimate and report HFC-23 emissions from HCFC-22 production) based on information received by the Ozone Secretariat from parties. These best practices to control emissions of HFC-23 are consistent with those used to control other emissions associated with chemical manufacturing. The summarised information from the 2025 TEAP report is included as an Annex to this report and has been updated to include new information received by the Ozone Secretariat from parties in response to decision XXXVII/2, paragraphs 2 and 3. In previous reports, TEAP has cited guidance for facilities in measuring, estimating, and reporting emissions under the UNFCCC Guidelines and from national governments.

MCTOC has carefully reviewed and presented the technical information provided by parties in their submissions in response to decisions XXXVI/3 and XXXVII/2, alongside the data submitted by parties under Article 7, which is included in Table 2.2. These data show some large variations in the average HFC-23 emissions per HCFC-22 plant. MCTOC is unable to fully explain the reason for these variations using the information provided by the parties.

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1 Introduction

1.1 Decision XXXVII/2: Emissions of HFC-23

Following discussion at the Thirty-Seventh Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer (MOP-37) of the information on HFC-23 emissions submitted by the Technology and Economic Assessment Panel (TEAP) and the Scientific Assessment Panel (SAP) in response to decision XXXVI/3, the parties agreed, in decision XXXVII/2 on Emissions of HFC-23:

2. To request the Technology and Economic Assessment Panel and the Scientific Assessment Panel to provide an update on emissions of HFC-23 to the Thirty-Eighth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, taking into account the information submitted by parties in response to decision XXXVI/3 and pursuant to paragraph 2 below and including the following:
   (d) Additional analysis of the discrepancy between reported emissions and those derived from atmospheric measurements, including the methodologies applied;
   (e) A description of the information and data sources used, identifying any gaps or limitations;
   (f) Additional information on methodologies adopted by parties for estimating and reporting HFC-23 emissions as well as best practices for improvements to minimize such emissions;
3. To invite parties that have HCFC-22 production facilities and did not submit information pursuant to decision XXXVI/3 to submit to the Ozone Secretariat, by 28 February 2026, on a voluntary basis, their current methodologies for estimating and reporting HFC-23 emissions from HCFC-22 production;
4. To invite relevant parties:
   (a) To report 2025 data, consistent with form 6 of the data reporting forms, on the amounts of HFC-23 generated, captured, destroyed and stored;
   (b) To examine, as appropriate, their HFC-23 emissions and the sources of those emissions and encourage scientific research institutions in their countries to undertake or collaborate internationally on research on their HFC-23 emissions and the sources of those emissions, and to report to the Ozone Secretariat new relevant information, if any.

This TEAP report responds to decision XXXVII/2.

Four parties, namely China, the European Union (EU), Peru and the Russian Federation, provided further information, as invited in decision XXXVII/2, and 14 parties reported data on production and emissions of HFC-23.[5] TEAP reviewed and considered this available information in preparing this report.

During the development of this report, TEAP coordinated with the SAP and included information provided by the SAP from its 2026 Assessment on updated estimates of emissions of HFC-23 derived from atmospheric measurements.[6]

[5] https://ozone.unep.org/hfc-23-emissions

[6] World Meteorological Organization (WMO). *Scientific Assessment of Ozone Depletion: 2026, GAW Report No. xxx*, WMO: Geneva, 2026. (In preparation)

1.2 TEAP's response to decision XXXVII/2

Given the focus of decision XXXVII/2 on updating the previous response by the TEAP to decision XXXVI/3, the Medical and Chemicals Technical Options Committee (MCTOC), with its relevant chemical production expertise, led the preparation of this report on behalf of the TEAP.

Reports by TEAP in response to decisions XXXV/7[7] and XXXVI/3[8] contained detailed information on HFC-23 emissions from chemical pathways used in the production of Annex C, Group I, or Annex F substances as well as brief information on other additional HFC-23 emissions, including from consumptive uses. MCTOC consulted experts within TEAP to address emissions from these sectors.

1.3 Development and structure of this report

MCTOC met to prepare this report from March until late August 2026, including during its face-to-face/hybrid meeting in April and online. To facilitate the drafting of this report, MCTOC formed a drafting sub-group of the chemical experts with a range of relevant industry expertise and geographic coverage. During August, a final draft report was reviewed by the full membership of MCTOC and TEAP, and SAP experts, followed by a final review of the report incorporating the feedback received.

The report responds to decision XXXVII/2 and includes, within the sections where possible, a description of the information and data sources used, identifying any gaps or limitations. It also includes additional contextual information on other HFC-23 generation and/or emissions, i.e., from chemical pathways used in the production of substances that are not Annex C, Group I, or Annex F substances, and from feedstock and consumptive uses. This additional contextual information was considered useful in understanding the relative importance of chemical pathways used in the production of Annex C, Group I, or Annex F substances that may generate emissions of HFC-23.

1.4 Explanation of terms

Several terms referred to in this report are explained further below and at relevant places within the report.

A *chemical pathway* (or reaction pathway) describes the specific selected starting materials/feedstocks used to be converted into the desired chemical product. The chemical pathway selected considers factors such as the yield and purity of the final product(s) and minimising unwanted side-products (i.e., by-products) and waste materials. There are other considerations in selecting commercially desirable chemical pathways, including plant design, engineering, safety, the impact of scaling up quantities, reaction time, raw material and feedstock availability and cost and intellectual property. For example, there are several chemical pathways used to produce HFC-152a; one chemical pathway uses vinyl chloride as starting material, and another uses acetylene.

A *chemical process* describes the mechanism for how chemicals are transformed or formed, defining its associated chemical reactions and chemical and/or physical conditions. For example, HFC-23 by-product can be generated via different chemical processes, with the potential for those chemical processes to occur across a range of different chemical pathways where the right mix of chemicals and conditions allows it (see Chapter 2).

A *by-product* is considered an ancillary product, which is created as the secondary result of a primary process to create an intended product. A by-product is created through chemical processes that are secondary to those creating the primary product. A by-product may be ancillary, but it is not

[7] UNEP 2024, *Report of the TEAP, Volume 5, Response to Decision XXXV/7: Emissions of HFC-23*, September 2024.

[8] UNEP 2025, *Report of the TEAP, Volume 2, Response to Decision XXXVI/3: Emissions of HFC-23*, September 2025.

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necessarily unwanted if it is commercially valuable and can be economically and efficiently separated from the primary product and any other by-products.

Generation is the formation of a chemical arising from a chemical process used in chemical production. For this report, generation is defined as the total HFC-23 produced as a by-product, without taking into account abatement of emissions (see Chapter 3).

An *emission* is considered as the release of substance into the environment, often describing gas releases of substance to atmosphere but also substance released in solids or liquids. For this report, emissions are defined as the total HFC-23 emitted from a facility that either uses HFC-23 as a feedstock or generates HFC-23 as a by-product, after any abatement (see Chapter 3). Although HFC-23 may be emitted via different routes, the dominant emission pathway is direct emissions to atmosphere.

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2 Update of information on the amount of HFC-23 generation and emission from facilities that manufacture Annex C, Group I, or Annex F substances

This section provides an update of the information that was reported in the 2025 TEAP response to the previous decision XXXVI/3 on the amount of HFC-23 generation and emissions from facilities that manufacture Annex C, Group I, or Annex F substances, the reporting of which is required under Article 7 of the Montreal Protocol.

The sources of information for the amounts of HFC-23 generation are the following:

- HFC-23 generation reported by parties on a voluntary basis, under Article 7 of the Montreal Protocol.
- Data submitted to the Multilateral Fund Executive Committee (ExCom) as part of project proposals to enable compliance with the HFC-23 by-product control obligations of the Kigali Amendment. Data for individual production units are also available. The May 2026 TEAP Replenishment Task Force Report summarises the information.[9]

The three main sources of information for the amounts of HFC-23 emissions are the following:

- HFC-23 emissions reported by parties, which is a mandatory report, under Article 7 of the Montreal Protocol
- Annual emissions derived from atmospheric monitoring, known as top-down emissions, as reported by the SAP, including updated information on global summed HFC-23 emissions for 2024 to be published in the 2026 SAP Assessment Report[10].
- Data submitted to ExCom as part of project proposals to enable compliance with the HFC-23 by-product control obligations of the Kigali Amendment. Data for individual production units are also available. The May 2026 TEAP Replenishment Task Force Report summarises the information.[11]

2.1 An update of information on the amount of HFC-23 generation from facilities that manufacture Annex C, Group I, and Annex F substances

2.1.1 Compilation of data on the amount of HFC-23 generation reported by parties

Data on HFC-23 generation reported by parties is an optional report under Article 7 of the Montreal Protocol. HFC-23 generation data are not reported for all parties that are known to produce HCFC-22.

Some parties would not have been expected to report optionally for each of these years (2019, 2020, 2021, 2022) because of the date on which the parties ratified the Kigali Amendment and associated

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[9] UNEP 2026, *Report of the TEAP, Volume 2: Assessment of the Funding Requirement for the Replenishment of the Multilateral Fund for the Period 2027-2029*, May 2026. Chapter 4, HFC production sector and HFC-23 by-product emission mitigation,.

[10] World Meteorological Organization (WMO). *Scientific Assessment of Ozone Depletion: 2026, GAW Report No. xxx*, WMO: Geneva, 2026. (In preparation)

[11] UNEP 2026, *Report of the TEAP, Volume 2: Assessment of the Funding Requirement for the Replenishment of the Multilateral Fund for the Period 2027-2029*, May 2026. Chapter 4, HFC production sector and HFC-23 by-product emission mitigation.

obligations. The data on the generation of HFC-23 are not published by the Ozone Secretariat for individual parties.

The consolidated quantities of HFC-23 generated from HCFC-22 production for those parties that reported data in 2023 and 2024 were 24,375.65 tonnes and 23,808.86 tonnes, respectively. The majority of the generated HFC-23 is not emitted, as shown in Section 2.2 below.

Data on annual HFC-23 emissions from facilities manufacturing Annex C, Group I substances (HCFCs) and Annex F substances are required to be reported by parties under paragraph 3 *ter* of Article 7 of the Montreal Protocol. The data in Table 2.1 are available on the Ozone Secretariat website.[12] The number of facilities is shown in brackets. The estimated current and recent historical locations of the HCFC-22 production facilities are provided in graphical form in Annex 3 of this report for information, based upon previous reports from the Clean Development Mechanism of UNFCCC, published addresses of manufacturing facilities and other sources.

Data on HFC-23 emissions are also reported to the United Nations Framework Convention on Climate Change in their National Inventory Reports or their Biennial Transparency Reports. However, it is not always possible to compare these data with the data reported under Article 7 of the Montreal Protocol because when reporting to UNFCCC, different parties use different methodological **IPCC tiers to estimate the HFC-23 production from HCFC-22 production. For example, some parties do not report the destruction of HFC-23 or the collection of HFC-23 for feedstock use when reporting emissions of HFC-23 to UNFCCC.**

The methodology used by the different parties for estimating HFC-23 emissions for reporting under Article 7 of the Montreal Protocol is not provided in sufficient detail to be confident that all parties use the same methodology and scope to estimate their HFC-23 emissions.

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[12] https://ozone.unep.org/hfc-23-emissions

Table 2.1 Quantities (in metric tonnes) of HFC-23 emissions reported[13] under Article 7 with the number of production facilities shown in brackets

	2019	2020	2021	2022	2023	2024
Argentina		36.14 (1)	33.31(1)	17.31 (1)	0 (1)	0 (1)
China		48.101 (19)	1,090 (20)	637.393 (21)	901.717 (23)	937.75 (23)
Democratic People's Republic of Korea	9.1 (1)	9.1 (1)	8.4 (1)	8.38 (1)	8.372 (1)	7.312 (1)
European Union	22.933 (3)	9.918 (3)	17.733 (3)	0.815 (4)	5.387 (4)	1.486 (4)
India			0 (5)	0 (5)	0 (5)	0 (NR)
Japan	0 (4)	9.307 (4)	8.644 (4)	0.0034 (4)	0.041 (4)	0.036 (3)
Mexico	111.89 (1)	39.28 (1)	128.52 (1)	31.887 (1)	0.0043 (1)	0.0004 (1)
Republic of Korea					0 (1)	0 (1)
Russian Federation			0 (1)	0 (1)	0 (2)	0.03 (1)
United States of America					43.5 (10)	56.67 (10)
TOTAL	**143.923**	**151.846**	**1,286.607**	**695.7784**	**959.0213**	**1,003.284**

Notes: The number of facilities is the total number of facilities that each party reported HFC-23 emissions data for, which includes HCFC-22 and other relevant Annex C Group 1 and Annex F production facilities.

Reported HFC-23 emissions data is not specifically linked to production data (whether production of HCFC-22 or another substance).

HFC-23 emissions can be from facilities that were not necessarily HCFC-22 production facilities.

2.2 Compilation of data on the quantities of HFC-23 emissions reported to ExCom

Five Article 5 parties (Argentina, China, India, the Democratic People's Republic of Korea (DPRK) and Mexico) report the quantities of HFC-23 emissions, to the Executive Committee of the Multilateral Fund. This is summarised in Table 2.2. These data are consistent with those reported by those parties under Article 7.

[13] Blanks imply that the information was not reported, while zeros are reported as such.

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Table 2.2 HFC-23 emissions reported to ExCom by countries reporting HFC-23 production and generation under the Kigali Amendment (tonnes)[14]

	2021	2022	2023	2024
Argentina	33.31	17.31	0	0
China	1089.95	637.39	901.72	937.75
India	0	0	0	0
DPRK	8.40	-	-	7.312
Mexico	128.52	31.89	0.0047	0.0004

2.3 Information on HFC-23 emissions, including from sources other than facilities that manufacture Annex C Group I or Annex F HFCs

This section provides additional contextual information on HFC-23 emissions, including from sources other than facilities that manufacture Annex C Group I and Annex F HFCs, such as feedstock and consumptive uses. While outside the scope of decision XXXVII/2 (and earlier decisions on which this updated report is based), this additional contextual information is considered useful in understanding the relative importance of HFC-23 emissions from chemical pathways used in the production of Annex C, Group I, or Annex F substances that may generate HFC-23 as a by-product.

TEAP has not identified any significant new sources of HFC-23 emissions that have started since 2015 or any changes in production processes or major growth in current uses that would result in the substantially higher emissions post-2014.

2.3.1 HFC-23 emissions derived from atmospheric monitoring

While global emissions derived from atmospheric observations peaked at 17,000 ± 1,000 tonnes per year in 2018 and 2019, they have since decreased and been relatively constant at 14,000 ± 1,000 tonnes per year in 2022, 2023, and 2024.[15]

2.3.2 HFC-23 by-product emissions from the production of TFE/HFP

As described in the MCTOC 2022 Assessment Report[16], although some TFE/HFP production facilities would have abatement technology, data are not available to enable an accurate estimate of global HFC-23 emissions from TFE/HFP production.

The MCTOC 2022 Assessment Report used indicative low to medium HFC-23 by-product generation rates for TFE/HFP production, based on HCFC-22 feedstock use, to estimate HFC-23 by-product emissions, without consideration of their possible abatement, of between 380–1,440 tonne, based on

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[14] The data for Argentina, China, India, DPRK and Mexico are cited from the ExCom documents "Country Programme Data and Prospects for Compliance." (UNEP/OzL.Pro/ExCom/91/8), UNEP/OzL.Pro/ExCom/93/8), UNEP/Ozl.Pro/ExCom/95/8, UNEP/OzL.Pro/ExCom/97/8)

[15] World Meteorological Organization (WMO). *Scientific Assessment of Ozone Depletion: 2026, GAW Report No. xxx*, WMO: Geneva, 2026. (In preparation).

[16] UNEP, 2022, *2022 Report of the Medical and Chemical Technical Options Committee, 2022 Assessment Report*, December 2022. Section 2.3.2, page 42.

HCFC-22 reported feedstock production in 2024 with 97% of this used for TFE/HFP production.[17] No further information has been received to change the application of the low and medium by-product generation rates. Taking into account possible abatement, and that the by-product generation rates are estimates, the total global HFC-23 by-product generation from TFE/HFP is estimated to be in the range 100–1,000 tonnes. This excludes the HFC-23 generation from the HCFC-22 production at integrated facilities and includes only generation associated with TFE and HFP production.

2.3.3 Emissions from the use of HFC-23 as feedstock

A main use of HFC-23 as feedstock is production of bromotrifluoromethane (Halon 1301), which is then used as a feedstock for fipronil and other chemical production.[18] HFC-23 emissions arise from this feedstock use; from the supply of the HFC-23 and from chemical processes where HFC-23 is used as feedstock. Feedstock production for internal use and imports is reported by parties, under Article 7. Some parties have not been required to report HFC data for each of these years (2019, 2020, 2021) due to the timing of reporting obligations, such as when parties ratified the Kigali Amendment.

In 2023, the available data of HFC-23 production for feedstock uses under Article 7 reporting shows for one party that the reported quantity of bromotrifluoromethane used as feedstock broadly matches the reported quantity of HFC-23 produced for feedstock, assuming this is the only use for HFC-23 feedstock. Another party reports significant bromotrifluoromethane production but no HFC-23 production or imports of HFC-23 for feedstock use. This party might be using a different chemical process to produce bromotrifluoromethane or considers the HFC-23 to be an intermediate. Other parties report HFC-23 production but no bromotrifluoromethane production, which suggests either bromotrifluoromethane is considered an intermediate or the HFC-23 is being used to produce different substance(s).

The total reported HFC-23 production for feedstock (for own use and imports) in 2023 is 707 tonnes, and in 2024 is 710 tonnes.[19] Applying the MCTOC most likely emission factor (3.6%)[20,21] for production, supply chain, and use of feedstock to the 2024 production quantity equates to estimated HFC-23 emissions of 26 tonnes.

2.3.4 HFC-23 by-product emissions from HCFC-22 plant waste and product streams

Most HFC-23 by-product will be released through the plant vent(s), and/or mitigated, on the site where the HFC-23 is generated. However, there is the possibility of a wide dispersal of the small percentage of HFC-23 generated that is entrained/contained within products and waste streams leaving the process where HFC-23 is generated. For example:

- Products including HCFCs, HFCs and co-produced HCl(aq.) have been found to contain up to ~0.04 wt.% of HFC-23. About 0.84 tonnes HCl is produced per tonne of HCFC-22 production. This HCl is typically absorbed water to form HCl (aq.) with a strength ranging

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[17] Reported 2020 HCFC-22 feedstock data are used, with 97% of this used for TFE/HFP production. As expected, calculated emissions of PFC-c-318 are slightly different to those inferred from atmospheric measurements. The global emission factor for HFC-23 from TFE/HFP will depend on the relative use of abatement technologies.

[18] CF_3 generated from bromotrifluoromethane can be introduced into a wide range of organic molecules by nucleophilic substitution to produce chemicals, including fipronil (insecticide), mefloquine (antimalarial), and DPP-IV inhibitor (antidiabetic).

[19] UNEP 2026, 2026 *TEAP Progress Report, Volume 1*, Table 5.2 Reported amounts of HFC used as feedstock in 2023 and 2024.

[20] UNEP, 2022, *2022 Report of the Medical and Chemical Technical Options Committee, 2022 Assessment Report*, December 2022.

[21] UNEP 2024, *2024 TEAP Progress Report, Volume 1*, Table 5-9, MCTOC emission factors for modern-day, regulated manufacturing from production, supply chain, and use of feedstock (by weight of production).

from 36–20 wt.%. This means that there could be as much as 4.2 tonnes of co-produced HCl (aq.) per tonne of HCFC-22 produced. As an example, assuming the HCl (aq.) from HCFC-22 production contained 0.02% by weight HFC-23 and was at an average strength of 28 wt.%, this would result in emissions of about 700 tonnes of HFC-23, from total reported HCFC-22 production in 2024, if there was no abatement before the HCl (aq.) was dispatched from the production site.

- HFC-23 contained as an impurity within HCFC or HFC products will likely be released to the atmosphere when the HCFC or HFC product is released, either during use (for example, from the bank of the product) or at end of life.
- HFC-23 contained within co-produced HCl (aq.) will slowly degas to atmosphere when the HCl (aq.) is transferred to a storage system that vents to atmosphere or during use (e.g., in metal pickling vats).
- Aqueous waste streams resulting from contact with process streams containing HFC-23 (e.g., in plant scrubbing systems) will contain a small quantity of HFC-23 (possibly up to 0.1 wt.%, although often considerably less) that will eventually enter the atmospheric compartment, either at the waste treatment plant or in the wider environment, e.g., river system into which the treated aqueous effluent is ultimately discharged under regulatory permit.

These small, but potentially widely distributed, HFC-23 emissions associated with the use of the products could manifest themselves as either a more generalised widespread HFC-23 emission or a localised point source HFC-23 emission, possibly both being a considerable distance from the HFC-23 by-product generating plant and not directly relatable to that plant's production timings.

2.3.5 Estimated emissions of HFC-23 as an impurity from emissions from the HCFC-22 bank

Banks are the total amount of substances contained in existing equipment, chemical stockpiles, foams, and other products, not yet released to the atmosphere. The HCFC-22 bank is discussed in the 2022 MCTOC Assessment Report[22]. Emissions of HCFC-22 from the bank are mainly due to leakage and end-of-life emissions from refrigeration and air-conditioning equipment. HFC-23 as an impurity in HCFC-22 refrigerant will also be emitted to atmosphere. HFC-23 emissions can be estimated from its concentration as an impurity in HCFC-22 and the reported emissions of HCFC-22.

Annual emissions of HCFC-22 in 2023 and 2024 are about 300,000 tonnes based on atmospheric observations.[23] Some of these emissions will result from use of HCFC-22 as a feedstock. The reported HCFC-22 production for feedstock use was 978,084 tonnes in 2023 and 990,395 tonnes in 2024[24]. Emissions of HCFC-22 due to feedstock use, by applying the MCTOC most likely emission factor (3.6%)[25,26] for production, supply chain, and use of feedstock, are estimated at about 35,000 tonnes for 2024. By subtracting the estimated feedstock emissions of 35,000 tonnes from total global emissions of HCFC-22, remaining emissions of approximately 265,000 tonnes HCFC-22 can be estimated to be resulting from emissions from the bank of HCFC-22 refrigerants. HFC-23 impurity in HCFC-22 used as refrigerant is typically <150 ppm. If it is assumed that all HCFC-22 emissions from the bank contain 100 ppm of HFC-23, then about 27 tonnes of HFC-23 emissions can be estimated from

[22] UNEP, 2022, *2022 Report of the Medical and Chemical Technical Options Committee, 2022 Assessment Report*, December 2022. Section 8.2.3.3, HCFC-22 banks and amounts reaching end-of-life.

[23] World Meteorological Organization (WMO). *Scientific Assessment of Ozone Depletion: 2026, GAW Report No. xxx*, WMO: Geneva, 2026. (In preparation).

[24] UNEP, 2026, *2026 TEAP Progress Report, Volume 1*, Table 5.1.

[25] UNEP, 2022, *2022 Report of the Medical and Chemical Technical Options Committee, 2022 Assessment Report*, December 2022.

[26] UNEP 2024, *2024 TEAP Progress Report, Volume 1*, Table 5-9, MCTOC emission factors for modern-day, regulated manufacturing from production, supply chain, and use of feedstock (by weight of production).

HCFC-22 bank emissions for 2024. HCFC-22 used as feedstock typically contains HFC-23 at much lower concentrations and HFC-23 contained in emissions of HCFC-22 from use as feedstock can be ignored.

2.3.6 HFC-23 emissions reported from electrochemical fluorination

Some data are available in CRF tables from submissions to UNFCCC by Annex I countries for HFC-23 emissions from chemical processes other than as a by-product of HCFC-22 production. Previous reports of fugitive HFC-23 emissions in the European Union (EU) were indicated to be from electrochemical fluorination processes, according to an EU member state in its national inventory report (NIR) submission to UNFCCC.[27] According to the 2026 EU submission received in response to decision XXXVII/2, a notable source in Belgium of HFC-23 emissions from electrochemical fluorination processes was significantly mitigated once identified and has subsequently ceased operation in 2025. Similar production facilities for that company in the United States also terminated operation at that time due to the company's publicly announced intention to discontinue producing all chemicals that fall under the PFAS definition by the end of 2025. Electrochemical fluorination is understood to be reducing, with associated HFC-23 emissions also expected to be trending downwards.[28]

2.3.7 Production and consumption of HFC-23 for emissive uses

There are three main industry sector uses of HFC-23 that result in potential emissions:

- Fire suppressant
- Low temperature refrigerant
- Etchant and chamber cleaning in semiconductor and electronics manufacturing

Use as fire suppressant and low temperature refrigerant creates a bank of installed equipment containing HFC-23. Emissions can occur during manufacture (filling), use, and at end-of-life. The use of HFC-23 as an etchant and for chamber cleaning results in emissions of unreacted HFC-23 that can be significantly reduced by implementation of emissions control technologies.

In 2024, the reported consumption of HFC-23, under Article 7 of the Montreal Protocol, was about 2,200 tonnes. Calculated consumption for HFC-23 is Production plus Imports minus Exports minus Feedstock imports minus Destruction. The 2,200 tonnes quantity excludes mandatory destruction of HFC-23 for by-product emissions from Annex C1 and Annex F production but includes any reported HFC-23 destroyed following use, for example, as refrigerant.

Meanwhile, 17 Article 5 parties reported to the Executive Committee of the Multilateral Fund total consumption of 1,581.62 metric tonnes of HFC-23 used in the fire fighting, refrigeration system manufacturing, refrigeration servicing, solvent, and other sectors in 2024. These countries were Brazil, China, Egypt, El Salvador, Eritrea, India, Indonesia, Malaysia, Maldives, Mexico, the Philippines, Seychelles, Sri Lanka, Suriname, Thailand, Türkiye, and Viet Nam.[29]

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[27] Belgium NIR submission 2023, section 4.3.2.7, Fluorochemical production (category 2B9), available at National Inventory Submissions 2023 | UNFCCC and Belgium. 2024 Common Reporting Table (CRT) worksheet Table 2(II).B-Hs1 available at https://unfccc.int/ghg-inventories-annex-i-parties/2024

[28] 3M News Center, 2022, *3M to Exit PFAS Manufacturing by the End of 2025*, December 20, 2022. https://news.3m.com/2022-12-20-3M-to-Exit-PFAS-Manufacturing-by-the-End-of-2025

[29] UNEP/OzL.Pro/ExCom/97/8.

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Other publicly available data is available. The HFC-23 production quotas publicly released by China have been above 2,300 tonnes per year since 2024.[30] [31] [32] The United States has published consumption of HFCs for 2024 as a requirement of the AIM Act.[33] with 110.8 tonnes of HFC-23 consumption, calculated according to reporting requirements under the Montreal Protocol. The EU's *Fluorinated greenhouse gases 2025* reported total supply of 36 tonnes HFC-23 to the EU market in 2024. This quantity does not take account of any HFC-23 destroyed.[34]

Publicly available annual greenhouse gas inventory data is reported to and compiled by the UNFCCC from national inventory reports (NIRs). Annex I parties[35] are required to submit NIRs of anthropogenic emissions by sources and removals by sinks of greenhouse gases. To prepare their NIRs, parties use the 2006 IPCC Guidelines, and any subsequent agreed version or refinement of the IPCC guidelines. Parties can currently use on a voluntary basis the Intergovernmental Panel on Climate Change 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Countries can take different approaches to compiling and/or estimating emissions for these inventories according to and within these guidelines. These guideline methodologies can differ from methodologies employed by TEAP, or others, in estimating emissions. No estimation technique will be perfect; different outputs are to be expected from different methodologies.

Table 2.3 summarises available consumption and emissions data in UNFCCC national submissions for those countries that reported more than 10 tonnes of reported calculated consumption (Article 7) of HFC-23 in 2024. The data for the most recent year is reported for each country, but the available data may not be complete depending on the whether the submission is a National Inventory Submission or first Biennial Transparency Report. Data is not available for all countries that reported more than 10 tonnes of calculated consumption.

[30] Notice on Issuing the 2024 Quotas for the Production, Use, and Import of Ozone-Depleting Substances and Hydrofluorocarbons

[31] Public Notice on the Production, Use, and Import Quota Issuance of Ozone-Depleting Substances and Hydrofluorocarbons for 2025 - Ministry of Ecology and Environment of the People's Republic of China

[32] Public Notice on the Production, Use, and Import Quota Issuance of Ozone-Depleting Substances and Hydrofluorocarbons for 2026 _ Ministry of Ecology and Environment of the People's Republic of China

[33] Expanded HFC Data | US EPA and https://www.epa.gov/climate-hfcs-reduction/hfc-data-hub/expanded-hfc-data#2023-Production

[34] *Fluorinated greenhouse gases 2025*, Data reported by companies on the production, import, export and destruction of fluorinated greenhouse gases in the European Union, 2007-2024, ETC CM Report 2025/05 available at ETC CM report 2025/05: Fluorinated greenhouse gases 2025 — Eionet Portal

[35] Annex I parties include the industrialized countries that were members of the OECD (Organisation for Economic Co-operation and Development) in 1992, plus countries with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States.

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Table 2.3 Reported HFC-23 consumption and emissions data taken from UNFCCC national submissions, and emission year

UNFCCC National submissions (tonnes)	Refrigeration		Fire Protection		Electronics	
	Consumption	Emissions	Consumption	Emissions	Consumption	Emissions
EU 2024	2.353	16.76	0	9.955		1.874
USA 2022		NA	9.45	2.51		25.23
Japan 2024		0	0	0.55	89.9	4.84
Republic of Korea 2022	32.72	33.71	263.92	87.9		62.82
Russian Federation 2024		26.66			0.6	0.02
China 2021	10	1.9				
Singapore 2022						9.33
Total Reported Emissions		79.03		100.915		104.114

Notes:

Reported data from UNFCCC national submissions are provided only for those countries that reported more than 10 tonnes of reported calculated consumption (Article 7) of HFC-23 in 2024.

The UNFCCC consumption may not be the same as the Article 7 reported consumption. Total reported emissions in Table 2.3 for each source (refrigeration, fire protection, and electronic) are likely to be incomplete as not all countries listed here have reported emissions for each source and there may be emissions from other countries not listed here.

While the data available through UNFCCC reporting is incomplete and for different years, this report integrates these estimates of HFC-23 emissions from sectoral uses with assessments by TEAP and its TOCs to provide the ranges of estimated HFC-23 emissions shown in Table 2.5. Information in the sections below have been taken from the previous TEAP reports and updated where new sources of information have become available.

2.3.7.1 Emissions of HFC-23 from use as fire suppressant

The 2022 FSTOC Assessment Report states it is not possible to estimate the amount of HFC-23 used in fire protection from atmospheric measurements. HFC-23 is typically limited to use in cold temperature applications. Only limited information on actual amounts of HFC-23 used in fire protection is available and indicates that it is typically small compared to HFC-227ea. FSTOC estimates HFC-23 is about 1% of HFC-227ea use. The model used by FSTOC for HFC-227ea provides estimated fire protection emissions of 5,250 metric tonnes and a global HFC-227ea fire protection bank of 168,000 metric tonnes for the end of 2022.[36]

Based on this indicative estimate, and assuming similar emission factors are applicable, HFC-23 fire protection emissions were estimated to be about 50 tonnes for the end of 2022, with a fire protection bank of about 1,700 tonnes.

2.3.7.2 Low temperature refrigerant

Due to its very low boiling point (-82°C), HFC-23 is used as a low temperature refrigerant.

The 2022 TOC Refrigeration, AC and Heat Pumps Assessment Report (RTOC 2022) discusses the use of HFC-23 in transport refrigeration (super freezers) and pharmaceutical applications.[37] There is only a very small consumption of HFC-23 in RACHP applications. It is only used in ultra-low temperature (ULT) refrigeration equipment (e.g., below -50°C) as the refrigerant in the low

[36] UNEP 2022, *2022 Fire Suppression Technical Options Committee Assessment Report*, Section 6.4.3, HFC-23 Estimates.

[37] UNEP 2023, *2022 Refrigeration, AC and Heat Pumps TOC Assessment Report*, Section 6.2.2, Marine containers, and Section 10.2.2, Cold storage.

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temperature stage of cascade refrigeration systems. For these applications HFC-23 can be used as a pure fluid or as a component in blends. One ULT use is small storage cabinets (similar to domestic refrigerators) for medical products that must be stored at ULT, e.g., vaccines, tissue samples etc.

These are factory-built sealed systems, so leakage is close to zero, but there could be emissions at end-of-life if refrigerant is not recovered. Other larger ULT systems, such as climate test chambers, could use these refrigerants and could have higher leakage rates if they are not factory-sealed systems, but there is little information about the size of this market.[38] RTOC 2022 reports that five to ten thousand so-called super freezers existed for the shipment of tuna at -60 °C; these units are a refrigerant cascade with HFC-134a in the high side and HFC-23 in the low side. Conventional containers have a refrigerant charge typically between 4.5 and 7.5 kg.[39]

2.3.7.3 Etchant and chamber cleaning in semiconductor and electronics manufacturing

No updated information is available for etchant and chamber cleaning in semiconductor and electronics manufacturing.

In the 2019 Intergovernmental Panel on Climate Change (IPCC) Refinement of the Reporting Guidelines for Greenhouse Gases, the default emission factor for HFCs used in plasma etching or chamber cleaning in semiconductor manufacturing ranged from 0.13 to 0.7, depending on the gas and wafer size. HFCs can also be produced as by-products from other process gases. HFC-23, HFC-32 and HFC-41 are all commonly produced as by-products during the etch process when fluorinated gases are used as the etchant. Out of the HFCs, HFC-23 is the by-product generally produced in the largest quantities (with by-product emission factors ranging from 0.002 to 0.03).

Global consumption of HFCs for electronics manufacturing has increased significantly since 2013. According to the World Semiconductor Council (WSC), since 2013, the average annual growth rate of HFC-23 consumption for semiconductor manufacturing (etching and chamber cleaning) has been approximately 15%, from a total global consumption of 277 tonnes in 2013 to 720 tonnes in 2020.

Emissions of HFC-23 from semiconductor manufacturing have increased from 0.9 MMTCO_2e in 2013 to 1.4 MMTCO_2e in 2020, with an average annual growth rate of 6%. This is a much smaller growth rate than the growth rate in consumption, indicating an increase in the percentage of HFC-23 destroyed by abatement systems. Therefore, emissions of HFC-23 were about 64 tonnes in 2013 and about 92 tonnes in 2020 using IPCC's Fourth Assessment Report (AR4) global warming potential (GWP) value for HFC-23 (14,800). Consumption and emissions are expected to have increased in recent years.

The use of fluorinated gases as etchant and for chamber cleaning in semiconductor and electronics manufacturing is also discussed in detail in the MCTOC 2022 Assessment Report.[40]

HFC-23 is commonly used for selective etching of silicon dioxide (SiO_2) and silicon nitride (SiN).[41] When HFC-23 (CHF_3) is used as the etching gas and silicon (Si) as the substrate to be etched, in reactive ion etching (RIE), the CHF_3 forms ions, such as CF_3+, and fluorine (F) radicals by electron collision. These active species arrive at the substrate surface and react with the Si surface to form

[38] Ray Gluckman, TEAP Senior Expert.

[39] US EPA Transitioning to low-GWP alternatives in transport refrigeration [Transitioning to Low-GWP Alternatives in Transport Refrigeration (epa.gov)].

[40] UNEP, 2022, *2022 Report of the Medical and Chemical Technical Options Committee, 2022 Assessment Report*, December 2022. Section 5, Semiconductor and other electronics manufacturing.

[41] Dhungana, S., Nordell, B. J., *et al.*, Combinatorial survey of fluorinated plasma etching in the silicon-oxygen-carbon-nitrogen-hydrogen system, 2016, *Journal of Vacuum Science & Technology A*, 34, 061302. https://doi.org/10.1116/1.4964648.

SiF_4, which is volatile, resulting in the Si being etched. Not all the fluorinated gas breaks down, or is consumed, in the plasma. Radicals and molecules can also recombine in the plasma. Unreacted gas (or recombined molecules) accounts for most emissions of fluorinated gases from electronics manufacturing. The rate of unreacted gases depends on the type of gas and process conditions. For HFC-23, the unreacted rate is 0.46. A small fraction of the gas will also be converted into fluorinated by-products; HFC-23 is generated as a by-product from other process gases, such as CF_4 (by-product formation rate: 0.04), C_3F_8 (0.0000012), c-C_4F_8 (0.022), and even NF_3 (0.0068) and SF_6 (0.0014)[42]. If the amount of fluorinated gas used for etching is known, the amount of HFC-23 by-product can be estimated with noted assumptions[43] (Table 2.4).

Table 2.4 Estimation of HFC-23 arising from etching equipment (before abatement)

Process gas used	Amount of use[44] (tonnes, 2021)	HFC-23 type, rate[45]	HFC-23 exiting the etching equipment before abatement (tonnes)
Conventional Gas			
HFC-23	696	Unreacted, 0.46	320.2
CF_4	2,552	By-product, 0.039	99.5
C_2F_6	696	By-product, 0.002	1.4
C_3F_8	232	By-product, 0.0000012	0.0
C_4F_8	1,160	By-product, 0.022	25.5
NF_3	16,240	By-product, 0.0068	26.5
SF_6	696	By-product, 0.0014	1.0
New Gases			
CH_2F_2	928	By-product, 0.057	16.7[46]
C_4F_6		By-product, 0.018	
C_5F_8		By-product, 0.0053	
C_4F_8O		By-product, NA	
		Total	490.8

[42] *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Chapter 6, p.6.47, Table 6.7. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/3_Volume3/19R_V3_Ch06_Electronics.pdf.

[43] WSC data were not available for 2021 for HFC-23 consumption; Fuji Keizai Corporation data for 2022 have been used instead. The two datasets (WSC data are reported by semiconductor manufacturers and Fuji Keizai Corp. data are marketing data) do not correlate for earlier years; however, both show an increasing trend. HFC-23 consumption data for 2021 from WSC, when available, are also likely to show an increasing trend from 2020 (720 tonnes) to 2021.

[44] World Semiconductor Council, 2021, *Joint Statement of the 25th Meeting of the World Semiconductor Council (WSC)* http://www.semiconductorcouncil.org/wp-content/uploads/2021/08/FINAL-25th-WSC-Joint-Statement_0602.pdf

[45] *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Chapter 6, Table 6.7. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/3_Volume3/19R_V3_Ch06_Electronics.pdf. For NF_3, only 24% of total global consumption was assumed to be used for non-remote plasmas clean processes, for which this emission rate is applicable.

[46] Assumed same as C_4F_6 for by-product rate (0.018) for CH_2F_2, C_5F_8 and C_4F_8O.

Emissions from electronics manufacturing consist of the unutilised portion of the process gas and gases formed as a by-product during the process from other process gases. Some facilities have implemented emissions control technologies that significantly reduce emissions of HFCs and other fluorinated gases during semiconductor manufacturing. Abatement and scrubbing of process emissions is considered best practice. Pollutant emissions are required to meet local regulatory standards.

Best Practice Guidance for Semiconductor PFC Emission Reduction was published in 2017, which is relevant as a reference for reducing HFC-23 emissions. The followings are some examples of the guidance[47,48,49,50]:

- Process recipe optimization— optimizing processes to consume less greenhouse gases.
- Gas replacement— replacing the gas with lower GWP or using more reactive gases in the process.
- Point of use abatement— an abatement system is used to reduce emission by destructing unreacted and by-product gas.

For abatement, there are several technologies to be applied:

- Cartridge— dry-bed passive scrubber with active media. The cartridge absorbs HFC and should be exchange before breakthrough.
- Plasma— decompose fluorinated gases to HF and CO_2.
- Combustion— incineration with fuel.
- Combination of the above technology.

Default destruction removal efficiency rate for HFC-23 for electronics industry process is 0.98. There are no available data for installation rate; however, using consumption reported to the WSC, the estimated emissions without abatement based on default emission factors and the reported actual emissions, it is estimated that 83% of the HFC-23 that is exiting the etching chambers passes through abatement systems.

2.4 Updated "bottom-up" estimate of global annual HFC-23 emissions

The following table presents an updated compilation of available most recent annual estimates of HFC-23 emissions, based on a combination of known sources and updated available information included in this report and related 2023, 2024 and 2025 TEAP reports. Some of these are broad estimates where further information is currently not available to improve their accuracy. The table is footnoted to elaborate the estimation methods and approaches and any relevant information sources.

[47] UNEP, 2022, *2022 Report of the Medical and Chemical Technical Options Committee, 2022 Assessment Report*, December 2022. Section 5, Semiconductor and other electronics manufacturing.

[48] *PFAS-Containing Fluorochemicals Used in Semiconductor Manufacturing Plasma-Enabled Etch and Deposition* (Semiconductor Industry Association). https://www.semiconductors.org/pfas-containing-fluorochemicals-used-in-semiconductor-manufacturing-plasma-enabled-etch-and-deposition/.

[49] World Semiconductor Council, 2017, *Best Practice Guidance for Semiconductor PFC Emission reduction*, May 2017. http://www.semiconductorcouncil.org/wp-content/uploads/2017/07/Best-Practice-Guidance-of-PFC-Emission-Reduction.pdf

[50] Beu, L., S Raoux, Y.C. Chang, M R Czerniak, F. Illuzzi, T. Kitagawa, D. Ottinger, et al. 2019. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Chapter 6 Electronics Industry Emissions, Table 6.16. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/3_Volume3/19R_V3_Ch06_Electronics.pdf

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Table 2.5 Compilation of reported and available most recent annual estimates of HFC-23 emissions from known emissions 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	
HCFC-22, other Annex C Group 1, and Annex F production (2024)[51]	~1,003
Estimated HFC-23 emissions	
TFE/HFP manufacture (estimated, 2023)[52]	~100–1,000
Other fluorochemical manufacturing (e.g., hexafluoroacetone/HFA) (see Note 2)	~70
Feedstock use (estimated based on A7 reported consumption data, 2024)[53]	~26
HCFC-22 plant waste and product streams (estimated, 2023)[54]	~10–1,000
Impurity released from HCFC-22 bank (estimated, 2024)[55]	~27
Electrochemical fluorination (estimated, 2020)[56]	~10–100
Fire protection, minimum quantity based on Table 2.3[57]	~100
Low temperature refrigeration, minimum quantity based on Table 2.3[58]	~80–100
Semiconductor/electronics manufacturing, minimum quantity based on Table 2.3 (WSC data, 2020, 92 tonnes)[59]	~100
Total reported and estimated HFC-23 emissions from known sources	~1,500–3,500[60]

Notes:

1) Estimated total reported emissions take into account the ranges in the Table and contains data reported under Article 7 and those estimated in this and previous TEAP reports. These are contemporaneous annual estimates for the recent years for which data is available or estimated, which is from 2020-2024.

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[51] The estimate is rounded from the total presented in Table 2.1. Reported HFC-23 emissions data is not specifically linked to production data, whether production of HCFC-22 or another Annex C or Annex F substance.

[52] See section 2.3.2. There is evidence that the pyrolysis of HCFC-22 to produce TFE/HFP does produce some HFC-23 as a by-product. The potential global HFC-23 emissions from this pyrolysis were estimated using a combination of an estimated HFC-23 generation rate (see annex 1) and the reported quantity of HCFC-22 consumed to produce TFE/HFP. The availability of data on the HFC-23 generation rate from this pyrolysis reaction is limited as is the extent to which any HFC-23 formed is destroyed, the uncertainty this limited availability of data causes is reflected in the estimated range of HFC-23 emissions. The estimated range of HFC-23 emissions takes into account possible abatement and that the by-product generation rates are estimates the total global HFC-23 by-product generation from TFE/HFP.

[53] See section 2.3.3.

[54] See section 2.3.4. In addition to the main process vents, where HFC-23 abatement is typically employed, HFC-23 is known to be able to leave an HCFC-22 production plant is various co-product and waste streams (as outlined in the September 2023 TEAP report and in Annex 1). The extent to which the HFC-23 content of these streams has been included in the reported HFC-23 emissions from HCFC-22 production is uncertain. This uncertainty, along with the degree of HFC-23 emission mitigation employed on these streams, is reflected in the large range of estimated HFC-23 emissions.

[55] See section 2.3.5.

[56] See section 2.3.6. Electrochemical fluorination is understood to be reducing; associated HFC-23 emissions will also be trending downwards. (https://news.3m.com/2022-12-20-3M-to-Exit-PFAS-Manufacturing-by-the-End-of-2025)

[57] See sections 2.3.7 and 2.3.7.1. TEAP estimated 50 tonnes of HFC-23 emissions from fire protection for 2022; the UNFCCC data are reported for 2022 and 2024.

[58] See sections 2.3.7 and 2.3.7.2. TEAP estimated 10–100 tonnes of HFC-23 emissions from low temperature refrigeration for 2020; the UNFCCC data are reported for 2021, 2022 and 2024.

[59] See sections 2.3.7 and 2.3.7.3. TEAP reported WSC estimates of 92 tonnes from semi-conductor/electronics manufacturing for 2020; the UNFCCC data are reported for 2022 and 2024.

[60] Rounded from 1,526–3,526 tonnes.

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2) Other fluorochemical manufacturing processes may also generate HFC-23. One example is hexafluoroacetone (HFA), which serves as a key starting material in the production of hexafluoroisopropanol (a precursor for sevoflurane), hexafluoroisobutene (HFIB, a fluoropolymer monomer), and 4,5-difluoro-2,2-bis(trifluoromethyl)-1,3-dioxole (PDD, also a fluoropolymer monomer).

Due to its toxicity, any unreacted HFA (estimated by MCTOC expert, to be less than 5% of total production) must be treated and destroyed in a scrubber system according to the reaction shown below. This destruction process may represent a potential source of HFC-23 emissions, if there is no abatement.

$CF_3C(=O)CF_3$ *(HFA)* $+ NaOH \rightarrow CF_3H + CF_3COONa$

Based on an annual HFA production volume of 3,243 tonnes in 2025,[61] *the theoretical upper limit of HFC-23 generation is estimated to be approximately 70 tonnes.*

2.5 Summary

There are differences between SAP and TEAP estimates of global HFC -23 emissions that cannot currently be explained.

While emissions derived from atmospheric observations peaked at 17,000 ± 1,000 tonnes per year in 2018 and 2019, they have since decreased and been relatively constant at 14,000 ± 1,000 tonnes per year in 2022, 2023, and 2024.[62]

The combined total of reported HFC-23 emissions as a by-product from the production of Annex C, Group I substances (HCFCs) and Annex F substances (HFCs) for 2024 and most recent available "bottom up"[63] estimate of annual HFC-23 emissions from known emissions sources is about 1,500–3,500 tonnes.

These estimates exclude the potential additional source of HFC-23 from the atmospheric degradation of HFCs, HFOs, and HCFOs in the atmosphere. An upper-limit of this degradation source is currently assessed to be about 200 tonnes per year, as reported by SAP.[64] This upper limit of HFC-23 produced through photochemical and ozonolysis reactions is currently only a minor contribution to the global HFC-23 emissions.

SAP has described the uncertainties in the derivation of "top-down" emissions estimates based on atmospheric observations. However, these uncertainties do not bridge the difference between the SAP "top-down" and TEAP "bottom-up" estimates.

Given the large difference between the "bottom-up" and "top-down" estimates, a question arises about the completeness of the data reported under Article 7 and whether it includes all sources of HFC-23 emissions. As noted earlier, the Article 7 reported data for HFC-23 emissions appear to be predominantly related to HCFC-22 production; it is not known if HFC-23 emissions have been reported for all relevant production. Paragraph 3 *ter* of Article 7 requires HFC-23 emissions to be reported from all production of Annex C, Group 1, and Annex F controlled substances.

One unknown/uncertainty associated with the reporting of HFC-23 emissions is how facilities are measuring HFC-23 emissions, including "…*among other things, amounts emitted from equipment leaks, process vents and destruction devices, but excluding amounts captured for use, destruction or*

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[61] 24 Chemical Research, 2026, Hexafluoroacetone (HFA) Market 2026, 24 Chemical Research, 2026. https://www.24chemicalresearch.com/reports/300165/hexafluoroacetone-market. Accessed August 13, 2026.

[62] World Meteorological Organization (WMO). *Scientific Assessment of Ozone Depletion: 2026, GAW Report No. xxx*, WMO: Geneva, 2026. (In preparation).

[63] Contemporaneous annual estimate for the recent years for which data is available or estimated, which is from 2020-2024.

[64] World Meteorological Organization (WMO). *Scientific Assessment of Ozone Depletion: 2026, GAW Report No. xxx*, WMO: Geneva, 2026. (In preparation).

storage".[65] Differences between process operators' emission estimation methodologies are likely to result in variations in how HFC-23 emissions estimates are derived. Guidance for facilities in measuring, estimating, and reporting emissions is available under the UNFCCC Guidelines and from national governments. Consideration of these approaches when measuring and reporting HFC-23 emissions may assist where not currently taken into account.

There are also unknowns and uncertainties surrounding the TEAP estimations for sources other than reported HFC-23 emissions from production of HCFC-22, other Annex C, Group 1, and Annex F controlled substances. However, inaccuracy in estimations of these emissions would be relatively small and unlikely to bridge the difference with atmospheric-derived emissions estimates.

TEAP has identified the major known industrial and use-related sources for which information is currently available. No additional known sources identified through this review appear capable individually or collectively, on available evidence, of bridging the difference.

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[65] Article 3, Calculation of control levels, paragraph 1(d), "Emissions of Annex F, Group II, substances generated in each facility that generates Annex C, Group I, or Annex F substances by including, among other things, amounts emitted from equipment leaks, process vents and destruction devices, but excluding amounts captured for use, destruction or storage."

3 Update on best practices available to measure, estimate, report and verify emissions of HFC-23 by-product

Decision XXXVI/3 and XXXVII/2 invited parties to provide information regarding best practices and guidelines available to measure, estimate, report and verify emissions of HFC-23 by-product from facilities that manufacture Annex C, Group I Substances (HCFCs) or Annex F Substances (HFCs).

The section has been updated from 2025 with information submitted by parties in response to decision XXXVII/2, with the addition of the technical specification for accounting methods and reporting of by-product trifluoromethane emission from chlorodifluoromethane production facility received from China only.

For information, the generic Best Practice Guidelines taken from TEAP's response to decision XXXIV/7 are re-published in Annex 2. In previous reports, TEAP cited guidance for facilities in measuring, estimating, and reporting emissions available under the UNFCCC Guidelines and from national governments.

The section summarises a sample of various measures implemented or being implemented by parties to measure, estimate, report and verify emissions of HFC-23 by-product as have been reported in response to decisions XXXVI/3 and XXXVII/2. This is presented under a series of headings to allow comparison. This summary is non-exhaustive. It should be noted that the measures reported by parties to the Ozone Secretariat are designed to meet their national and regional reporting requirements under their national and regional regulatory regimes.

According to the terms of reference for the TEAP in the Annex to decision XXIV/8, "*The tasks undertaken by the Technology and Economic Assessment Panel (TEAP) are those specified in Article 6 of the Montreal Protocol in addition to those requested from time to time at Meetings of the Parties. TEAP analyses and presents technical information and recommendations when specifically requested. It does not evaluate policy issues and does not recommend policy. TEAP presents technical and economic information relevant to policy. Furthermore, TEAP does not judge the merit or success of national plans, strategies, or regulations.*" TEAP and its MCTOC have followed these terms of reference in responding to decision XXXVII/2 and preparing this report.

MCTOC has carefully reviewed and presented the technical information provided by parties in their submissions in response to decisions XXXVI/3 and XXXVII/2, alongside the data submitted by parties under Article 7 included in Table 2.2. These data show some large variations in the average HFC-23 emissions per HCFC-22 plant. MCTOC is unable to fully explain the reason for these variations using the information provided by the parties.

Possible contributory reasons for these variations could include differences in plant capacity and throughput; difference in plant design; differences in HFC-23 emission estimation methodology and scope; differences in plant operational history during the year (e.g., known loss of containment); and differences in the DRE of the destruction facility.

For example, it is not unreasonable for an operator only to have a limited number of specified emission points that are routinely monitored under their environmental permit and if all of these emission points contain little or no HFC-23 (and, for instance, the operator takes the view that if the HFC-23 is below the level of detection then the HFC-23 level is zero), there will be very low reported emissions; however, this may not be an accurate reflection the total HFC-23 emissions of the plant.

Another example could be if the operator only measures the main plant vent quarterly and does not check for HFC-23 in HCl stock tank vents, waste aqueous streams, etc., then it is quite conceivable that the operator could report no HFC-23 if on all 4 occasions when the HFC-23 content of the vent is

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being measured, the HFC-23 stream is being directed to the incinerator instead. This does not mean that the reporting is incorrect; it is more likely to indicate that the methodologies and scope of how the HFC-23 emission are estimated/measured may not identify and include all potential emissions. The submissions received from parties do not allow MCTOC to confirm these details. This can only be verified by inspection at individual facilities by operators and/or national authorities in accordance with the specific requirements of local regulatory controls.

While the Executive Committee of the Multilateral Fund (ExCom) has not specified requirements regarding methodologies for reporting HFC-23 emissions (from HCFC-22 production), it has reported some information on practices that might be useful:

- HFC-23 by-product emission control projects funded under the MLF include a requirement for an independent verification when submitting a request for a funding tranche. For an example, see paragraphs 43 to 47 of the project requesting the second tranche for the project to control and phase-out of HFC-23 emissions in production of HCFC-22 at Quimobásicos available here: https://www.multilateralfund.org/api/drupal-documents/download/file/f68a92e3-6745-4b4b-8b77-b109591c2da8?filename=9234.pdf
- Information on the verification for the project in Argentina to control emissions of HFC-23 by-project at FIASA can be found in paragraphs 50-51 and 58-60 of document https://www.multilateralfund.org/api/drupal-documents/download/file/7c6a9767-1e52-4733-9243-78fced9ec08e?filename=9736.pdf. The document also notes that FIASA staff regularly monitored the performance of the incinerator and completed maintenance and adjustments as needed, with emissions monitoring carried out weekly. Controlled shutdowns of the incinerator occurred during holidays, power outages, maintenance, and sampling, and from February to May 2024, minor adjustments were made to the incinerator such as valve cleanings and flowmeter and controller calibrations.
- Both above documents also have information related to possible fugitive emissions.
- Similar to the above, there is information related to emissions of HFC-23 by-product from China's HPPMP, including based on what is included in verification reports submitted under that project; A description of practices to monitor HFC-23 as of the 79th meeting of the ExCom, in China can be found in paragraphs 52- 57 of https://www.multilateralfund.org/api/drupal-documents/download/file/897e2a93-2d7c-4bab-9c6a-3ad5c220fc33?filename=7948.pdf.

In addition, decision 89/7(c), wherein the ExCom decided, when approving projects to control HFC-23 by-product emissions from production lines that would continue to produce the relevant Annex C, Group I or Annex F substance after the completion of the project, to invite the relevant Article 5 country to consider requesting additional funding for independent verification of the HFC-23 by-product generated, destroyed, sold, stored and emitted, under the subsequent stage of its HCFC phase-out management plan, until approval of its Kigali HFC implementation plan, at which time verification would continue under that plan.

3.1 Estimation/calculation of HFC-23 generation and/or emissions

3.1.1 China

To fulfil the obligations under the Kigali Amendment regarding the control of by-product HFC-23 emission and data reporting, and to standardise the accounting and reporting of by-product HFC-23 emission by enterprises, the Ministry of Ecology and Environment (MEE) issued the *Technical Specification for Accounting Methods and Reporting of By-product Trifluoromethane Emission from Chlorodifluoromethane Production Facility* (hereinafter referred to as the technical specification) in December 2025, which took effect on March 1, 2026.

The technical specification stipulates the accounting methods and reporting requirements for by-product HFC-23 emission from HCFC-22 production facilities, including working procedures, accounting boundaries, accounting methods, monitoring reports, emission reports, quality control and quality management, etc. The accounting methods for the generation volume and emission volume of by-product HFC-23 are as follows:

A.1 Calculation of HFC-23 generation

The quantity of by-product HFC-23 generated shall be calculated using the measurement method or the mass balance calculation method.

A.1.1 Measurement method

On a daily basis, enterprise collects samples from the top of reflux tower in the HCFC-22 reaction unit, and calculates the ratio of by-product HFC-23 to HCFC-22 based on chromatographic analysis results. The quantity of HFC-23 generation is then calculated by multiplying the HCFC-22 production, corrected by the loss correction factor, by this ratio. The calculation formula is as follows:

HFC-23 generation = HCFC-22 production * (1+ loss correction factor)* HFC-23/ HCFC-22 content ratio

A.1.2 Mass balance calculation method

The amount of chloroform ($CHCl_3$) consumed in the generation of HFC-23 is calculated based on the total consumption of the raw material $CHCl_3$ inputted into the HCFC-22 production facilities, the amount of $CHCl_3$ corresponding to produce HCFC-22, the amount of $CHCl_3$ corresponding to the by-product HCFC-21, and the system loss of $CHCl_3$. The quantity of HFC-23 generated is then estimated by mass balance calculation. The calculation formula is as follows:

HFC-23 generation = $CHCl_3$ consumption corresponding to HFC-23* molecular weight of HFC-23/ molecular weight of CHCl3.

(The molecular weight of HFC-23 is 70.0, and molecular weight of $CHCl_3$ is 119.5.)

A.2 Calculation of HFC-23 emissions

HFC-23 emissions are equal to HFC-23 generation minus HFC-23 disposal where HFC-23 disposal includes net storage, conversion, sales, and destruction of HFC-23.

B. Training on the technical specification

To further strengthen the management of by-product HFC-23 emissions and ensure the implementation of the technical specifications, MEE organized a training workshop on the technical specifications in Shandong in February 2026.

More than 120 participants attended the training, including managers in charge, production process technicians, and testing and monitoring technicians from all HFC-23 by-product enterprises, as well as officers from provincial and municipal ecological and environmental departments and environmental law enforcement departments where the enterprises are located.

The workshop provided a detailed interpretation of the technical specifications and introduced the key technical points for sampling, monitoring and quality control of by-product HFC-23. Technical staff from HFC-23 by-product enterprises held in-depth exchanges and discussions on how to implement the technical specifications.

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During the training, on-site teaching on HFC-23 supervision was also organized at Shandong Dongyue Green Cooling Technology Co., Ltd. Participants visited the HFC-23 sampling point, incineration facilities, DCS control room, chromatographic analysis laboratory and other sites on the spot. It helped participants gain a thorough understanding of relevant management requirements and comprehensively improved the level of HFC-23 emission supervision.

3.1.2 European Union

In accordance with the new EU Regulation (EU) 2024/1244 of the European Parliament and the Council, operators use the best available information when preparing the emission reports. Operators will determine the data through measurements. If the measurements do not lead to the best available information, or if they are not suitable or technically and economically feasible, operators will determine the data through calculations. If neither measurements nor calculations are feasible, operators may estimate the data. The information may include monitoring data, emission factors, mass balance equations, indirect monitoring, or other calculations, technical assessments, and other methods, and, where available, be in line with internationally recognised procedures. This new methodology approach is introduced by the latest revision of Regulation (EU) 2024/1244 and will apply from January 1, 2028. Until then the previous regulation still applies (2006/166). How the reporting by operators should be carried out until January 1, 2028 is described in Article 5, Paragraphs 1 to 5.[66]

3.1.3 India

Current methodology used by HCFC-22 producers in India for estimating reporting of HFC-23 emissions from HCFC-22 production:

- The entire system starting from generation to storage including gas-based incineration is in a closed loop.
- HFC-23 generated in HCFC-22 plant is sent for storage through a pipeline. The HFC-23 is stored in a pressurized vessel before it is sent for waste incineration through a pipeline. This ensures that there is no leakage of HFC-23 from the storage tank or during the transfer.
- Thereafter the incineration happens in a thermal oxidation with gas residence time not less than 2 seconds and at temperature of 1100°C plant ,which ensures its complete destruction of hazardous waste . The operation is through Distributed Control system (DCS) with full interlock logic, which is regularly monitored.
- In some plants, HFC-23 is directly fed into the incinerator without storage, where the incinerator is operated continuously and round the clock. There is also arrangement for liquification of HFC-23 and stored in tank in case of any stoppage of incinerator.
- The methodology used for estimating and reporting of HFC-23 emissions from HCFC-22 production is as follows: Quantity sent for incineration + closing stock – opening stock. The quantity sent for incineration is measured by flow transmitters and difference in the opening and closing stocks.

3.1.4 United States of America

In developing any required report, each producer of HFC-23 must abide by the following monitoring and quality assurance and control provisions:

- (A) To calculate the quantities of HFC-23 generated and captured for any use, generated and

[66] EUR-Lex - 2006/166 Regulation10. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006R0166

captured for destruction, used for feedstock without prior capture, and destroyed without prior capture, facilities shall comply with the monitoring methods and quality assurance and control requirements set forth at 40 CFR 98.414 and the calculation methods set forth at 40 CFR 98.413, except 40 CFR 98.414(p) shall not apply.

- (B) To calculate the quantity of HFC-23 emitted, facilities shall comply with the monitoring methods and quality assurance and control requirements set forth at 40 CFR 98.124 and the calculation methods set forth at 40 CFR 98.123.

3.2 Annual verification

3.2.1 China

Since 2021, MEE has annually organised experts to conduct on-site independent verification of HFC-23 by-product data for all HCFC-22 production enterprises in China. Technical experts verify the monitoring and measurement, the disposal methods and the operation status of the destruction facilities of HFC-23. Financial experts verify the sales and inventory of HFC-23. Through verifying the amount of HFC-23 generation, storage, sales and destruction, the annual emission of HFC-23 could be estimated.

MEE has been organising technical and financial experts to conduct annual on-site verification of HFCs production and by-product enterprises since 2021. Information from the annual verification serves as the data source of A7 data reporting. Based on the above two methods, technical experts will make specific adjustments to the estimation of HFC-23 generation based on their personal technical experience and the production equipment situation of each enterprise.

If an HCFC-22 production enterprise conducts daily measurements of HFC-23 and HCFC-22 in reactors, and the measured data is relatively stable, then the measured data analysis method is generally used to estimate the generation of HFC-23. If daily measurements are not carried out (some enterprises consider that the mixed gas at the sampling points contains hazardous hydrofluoric acid, leading to methodological caution) or the data could not meet the requirements of the measured data analysis method, the mass balance calculation method will be used to estimate the generation of HFC-23. However, since there is no technical specification for the estimation method of HFC-23 emissions, technical experts can adopt appropriate and feasible estimation methods contextually based on the specific situation of enterprises.

3.2.2 European Union

Reporting by companies is subject to independent verification by auditors pursuant to Art. 26(8) of the F-gas Regulation. Such verification is required above a threshold of 1,000 tonnes CO_2e of HFCs placed on the EU market. The independent auditor needs to confirm the veracity of the company report at a reasonable level of assurance. Auditors must be accredited either (i) under the ETS Directive (Directive 2003/87/EC[67]), or (ii) to verify financial statements in accordance with the legislation of the Member State concerned. Starting this year on reporting for the year 2024 this verification is also carried out within and as part of the reporting web interface (see above).

A public report of aggregated data is published on a yearly basis.[68.]

[67] https://eur-lex.europa.eu/eli/dir/2003/87/oj/eng

[68] https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/documentation/reports_en

3.3 Regulation and enforcement

3.3.1 China

In September 2021, MEE issued the *Notification on HFC-23 by-product Emission Control*, to clarify the requirements of emission control and corporate compliance obligations. The Notification specifies the following: HFC-23 by-product should be destroyed to the extent practicable using the destruction technologies approved by the Montreal Protocol, as well as the relevant data reporting requirements; enterprises are required to maintain operational records for HFC-23 by-production and destruction facilities, including monitoring and measuring the amount of HFC-23 generation, destruction, storage, usage and sales; measures are required to prevent the direct emission of HFC-23 during the shutdown of HFC-23 destruction facilities and abnormal operation of recovery, storage, and destruction facilities; enterprises are encouraged to reduce the generation rate of HFC-23 by-product, and develop and promote resource utilisation technologies for feedstock use of HFC-23. The Notification also clarifies supervision responsibilities of ecological and environmental authorities at all levels.

Furthermore, MEE has implemented quota management for HFC-23 produced and sold for controlled use (including by-production) since 2024.

To fulfil the obligations under the Kigali Amendment regarding the control of by-product HFC-23 emission and data reporting, and to standardise the accounting and reporting of by-product HFC-23 emission by enterprises, the Ministry of Ecology and Environment (MEE) issued the *Technical Specification for Accounting Methods and Reporting of By-product Trifluoromethane Emission from Chlorodifluoromethane Production Facility* (hereinafter referred to as the technical specification) in December 2025, which took effect on March 1, 2026.

The technical specification stipulates the accounting methods and reporting requirements for by-product HFC-23 emission from HCFC-22 production facilities, including working procedures, accounting boundaries, accounting methods, monitoring reports, emission reports, quality control and quality management, etc.

3.3.2 European Union

There are strict legal obligations to prevent emissions of HFC-23. Article 4 of the F-gas Regulation prohibits all intentional release where not technically necessary for the intended use. In case it is technically necessary then all measures technically or economically feasible to prevent, to the extent possible, the release to the atmosphere, including by recapturing the gas, must be taken. During the production (including by-production), storage, transport and transfer of HFC-23 from one container or system to another, to equipment or to a facility, the undertaking must take all necessary precautions to limit release of HFC-23 to the greatest extent possible. Any leakage detected must be repaired without undue delay.

Article 29 of the F-gas Regulation foresees that Member States shall conduct inspections on the compliance of undertakings with the Regulation, following a risk-based approach. Article 31 establishes that Member States shall lay down the rules on penalties applicable to infringements of the provisions of this Regulation and shall take all measures necessary to ensure that they are implemented. Similar provisions are stipulated by the ODS Regulation (Regulation (EU) 2024/590). Only a few Member States have HCFC and HFC production facilities today.

It is in particular prohibited to place on the market any fluorinated greenhouse gas (as listed in the F-gas Regulation) or ozone-depleting substances (as listed in the ODS Regulation[69]), unless the

[69] Regulation (EU) 2024/590 of the European Parliament and of the Council of 7 February 2024 on substances that deplete the ozone layer. https://eur-lex.europa.eu/eli/reg/2024/590/oj/eng

producer or importer provides evidence to the competent authority of a Member State that any HFC-23, produced as a by-product during the production process of fluorinated greenhouse gases or ozone-depleting substances, including during the production of feedstock for the production of those gases, has been destroyed or recovered for subsequent use, using best available techniques (Art. 4(6) of the F-gas Regulation and Art. 15(4) of the Ozone Regulation).

For the purpose of providing that evidence, producers and importers shall draw up a declaration of conformity, accompanied by supporting documentation:

(a) establishing the origin of the fluorinated greenhouse gases to be placed on the market;

(b) identifying the production facility of origin of the fluorinated greenhouse gases to be placed on the market, including an identification of those facilities of origin of any precursor substances that involve the generation of R-22 as part of the production process to produce the fluorinated greenhouse gases to be placed on the market;

(c) proving the availability and operation of the abatement technology at the facilities of origin equivalent to UNFCCC-approved baseline methodology AM0001 for incineration of trifluoromethane waste streams or proving the capture and destruction methodology that ensured that emissions of HFC-23 are destroyed in accordance with the requirements under the Protocol;

(d) on any additional information facilitating the tracking of the fluorinated greenhouse gas prior to import.

Destruction of HFC-23, and any products and equipment containing this gas, must use a technology approved by the Parties to the Protocol.

3.3.3 India

In 2016, India made an internal commitment requiring enterprises to mitigate emissions through incineration/destruction of HFC-23 by-product.

3.3.4 United States of America

The US Regulations are codified in the U.S. Code of Federal Regulations (CFR) at 40 CFR 84.31(b)(4)(iv) (https://www.ecfr.gov/current/title-40/part-84#p-84.31(b)(4)(iv)).

That paragraph contains references to methodologies that are found at:

40 CFR 98.123 (https://www.ecfr.gov/current/title-40/section-98.123);
40 CFR 98.124 (https://www.ecfr.gov/current/title-40/section-98.124);
40 CFR 98.413 (https://www.ecfr.gov/current/title-40/section-98.413); and
40 CFR 98.414 (https://www.ecfr.gov/current/title-40/section-98.414)

The USA EPA established requirements for all entities producing HFC-23 to control these emissions (40 CFR 84.27). Specifically, the EPA requires under 40 CFR 84.27 that no later than October 1, 2022, no more than 0.1 percent 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.

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3.4 Reporting

3.4.1 China

To fulfil the obligations under the Kigali Amendment regarding the control of by-product HFC-23 emission and data reporting, and to standardize the accounting and reporting of by-product HFC-23 emission by enterprises, the Ministry of Ecology and Environment (MEE) issued the *Technical Specification for Accounting Methods and Reporting of By-product Trifluoromethane Emission from Chlorodifluoromethane Production Facility* (hereinafter referred to as the technical specification) in December 2025, which took effect on March 1, 2026.

The technical specification stipulates the accounting methods and reporting requirements for by-product HFC-23 emission from HCFC-22 production facilities, including working procedures, accounting boundaries, accounting methods, monitoring reports, emission reports, quality control and quality management, etc.

3.4.2 European Union

Obligatory reporting on HFC-23 emissions is done in all 27 EU Member States pursuant to sectoral EU legislation such as:

- **Regulation (EU) 2024/573** of the European Parliament and of the Council of 11 March 2024 on fluorinated greenhouse gases (the so-called F-gas Regulation). The newly revised Regulation[70] requires the reporting of emissions of HFC-23 by producers of HFCs and other fluorinated greenhouse gases, the details of which are further specified in Commission Implementing **Regulation (EU) 2024/2195**[71]. The reporting data must be provided by producers annually in order to allow the derivation of HFC-23 emissions using the calculation: 1Aa (*production not captured*) -1A_a (*production destroyed without previous capture*) -1C_a1 (*production used for feedstock without previous capture*).

The annual obligatory company reporting on HFC-23 emissions (and other data on HFCs) in the EU is carried out via a highly sophisticated online questionnaire for this purpose operated by the European Environment Agency (EEA) for the European Commission. All reported information is stored in a database via a web interface that employs automatic quality checks on all submissions, followed by thorough manual quality checks. An FAQ and a user manual are available to companies to assist them in filling out the reporting web interface[72].

3.4.3 United States of America

Additional Requirements for producers of HFC-23

(i) Each producer of HFC-23 must include the following additional information in their one-time report in paragraph (b)(1) of this section:

  (A) Information on the capacity to produce the intended chemical on the line on which HFC-23 is produced;

[70] Under the EU Treaties, Regulations are directly applicable laws, creating rights and obligations for individuals, organisation and the Member States. Directives are only binding for Member States, setting policy objectives that need be transposed in their national legislation to create legal effects for individuals.

[71] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R2195

[72] https://bdr.eionet.europa.eu/help/fgases

(B) A description of actions taken at the facility to control the generation of HFC-23 and its emissions;

(C) Identification of approved destruction technology and its location intended for use for HFC-23 destruction;

(D) A copy of the destruction removal efficiency report associated with the destruction technology; and

(E) Within 60 days of any change in the information specified in the above report, the producer must submit a report specifying the changes to the relevant Agency official.

(ii) Each producer of HFC-23 must include the following additional information in their fourth quarter report:

(A) Annual facility-level data on HFC-23 (in metric tons) on amounts: Emitted; generated; generated and captured for any purpose; generated and captured for consumptive use; generated and captured for feedstock use in the United States; generated and captured for destruction; used for feedstock without prior capture; and destroyed without prior capture.

(B) [Reserved]

(iii) If captured HFC-23 is destroyed in a subsequent control period, producers must submit records to EPA indicating the HFC-23 has been destroyed in their next quarterly report.

3.5 Specific Best Practice indicated in submissions

3.5.1 European Union

The *Industrial Emission (IED 2.0; Directive 2024/1785) Directive* establishes the main principles for permitting and control of large industrial installations at local level, according to the legislation adopted by the Member States for implementing its objectives. The Directive follows an integrated approach and the application of best available techniques (BAT). BAT is the most effective techniques to achieve a high level of environmental protection, considering the costs and benefits.

On this basis, local authorities are issuing permits defining the legal responsibilities for the operators of relevant installations. The rules governing the information exchange, including data collection, procedures for drawing up BREFs, quality assurance and the handling of confidential business information are embedded into law under Commission Implementing Decision 2012/119/EU. This 'BREF guidance' provides all information on what is commonly referred to as the 'Sevilla process[73]'.

The BREFs produced by the European IPPC Bureau cover large-scale agro-industrial activities included in Annex I to the Industrial Emissions Directive 2.0; i.e., over 75,000 installations EU-wide. Each BREF contains a specific chapter on BAT conclusions, which comprise a short description of the best available techniques identified, their applicability and associated emission or consumption levels. BAT conclusions are subsequently adopted by a Committee procedure and published in the Official Journal of the EU. They provide the reference for setting emission limit values and issuing operating permits for industrial installations in EU Member States.

[73] The exchange of information in best available techniques takes place between the EU Member States, industries concerned and environmental NGOs. This is the so-called Sevilla Process.

The BREFs can be accessed here.[74] Relevant BAT conclusion for the emissions of HFC-23 are e.g., found in BAT 23 in the BAT conclusion document for Common Waste Gas.

Management and Treatment Systems in the Chemical Sector[75] and the corresponding BAT reference document (BREF)[76]. In particular the sections on channelled emissions to air (General techniques: 4.1.3.1, BAT 4-6), organic compounds: 4.1.3.3, BAT 9-10) and diffuse emissions (3.4.1, 3.4.2.4, 3.4.2.5, 3.4.2.6, 3.4.4, 3.4.5) are relevant.

The EU has provided information from a company in Italy that outlined the use of these BATs and good practices used:

The details of best available techniques applied generally are the LVOC (Large Volume Organic Compounds) and the WGC (Common Waste Gas Management and Treatment Systems in the Chemical Sector). The planned intervention for the valorisation of fluorinated streams for the production of HF falls within the scope of the BATC LVOC (Large Volume Organic Compounds), which has been in force since December 2017.

The document states:

- BAT 9: To reduce the pollutant load of gaseous emissions to be subjected to final treatment and to increase energy efficiency, the BAT is to direct process gas streams with sufficient calorific value to a combustion unit.
- Based on the Common Waste Gas Management and Treatment Systems in the Chemical Sector, effective from December 2022, the following Best Available Techniques (BAT) are in force:
  - BAT 10: In order to increase energy efficiency and to reduce the mass flow of organic compounds sent to the final waste gas treatment, BAT is to process off-gases with a sufficient calorific value to a combustion unit that is, if technically possible, combined with heat recovery. HFC-23 has a combustion heat not negligible.
  - BAT 19: To prevent or, where that is not practicable, to reduce diffuse VOC emissions to air, the BAT is to develop and implement a management system for diffuse VOC emissions as part of the environmental management system
  - BAT 23: To prevent or, where that is not practicable, to reduce diffuse VOC emissions to air, the BAT is to employ a combination of the techniques listed below, following the specified order of priority.[...] A set of high technical design standards ensures high tightening capacity, proper mechanical design and integrity preventive controls, routinary maintenance plans. Machineries are designed to ensure high integrity.

To effectively reduce emissions during the production, distribution, storage, handling, packaging, and use of ozone depleting substances as feedstock, the following practices and methodologies can be implemented:

1. Design and Engineering Controls: Implement design strategies that minimize potential emission sources, such as reducing detachable couplings and ensuring high-integrity equipment that is compatible with the chemical-physical characteristics of the substances.
2. Containment and Process Controls: Utilize containment elements to confine process

[74] BAT reference documents | EU-BRITE

[75] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022D2427

[76] https://bureau-industrial-transformation.jrc.ec.europa.eu/sites/default/files/2023-01/WGC_BREF_2023_for_publishing%20ISSN%201831-9424_final_1_revised.pdf

capacities, especially during operations like loading and unloading, to prevent diffuse emissions. For example, loading and unloading operation are buffered to process, without gaseous emissions

3. Maintenance and Inspection: Establish rigorous maintenance activities that ensure access to equipment for inspection, allowing for timely detection and repair of leaks. This includes adhering to preventive and predictive maintenance programmes. For example: periodic turn around shot down to implement preventive maintenance
4. Leak Detection and Repair (LDAR) Programs: Maintain an active LDAR program in accordance with industry standards and regulations, such as UNI EN 15446:2008 and EPA guidelines, to promptly address any detected leaks. LDAR performed twice per year.
5. Emission Prevention and Treatment: Design processes to prevent the generation of emissions, favouring the recovery of substances within production cycles or their transfer for appropriate abatement treatments. For example: HFC-23 recovered and sent to HFA and SolSpar production
6. Construction and Commissioning Procedures: Follow updated industrial standards during construction and assembly and implement stringent commissioning procedures to verify compliance with design requirements, including conducting leak tests before start-up. Start-up procedures and Pre Start-up Safety Review for new installations are in place.

By integrating these practices and methodologies, emissions of ozone-depleting substances can be effectively minimised.

3.5.1 India

Best practice technologies being followed by Indian Producers to reduce HFC-23 emissions.

- A well-designed distillation column with high efficiency packing to separate out HFC-23 from HCFC-22.
- HFC-23 generated is stored in a pressurised vessel which has a vent condenser with recovery,
- Storage tank load cells are calibrated at a regular frequency,
- Regular leak checks/detection of storage tank and transfer lines,
- Monitoring through flow meters (FT) for transfers to thermal oxidation plant and zero check of these FT every week. Also, FT is calibrated every 6 months,
- The HFC-23 is incinerated in a thermal oxidation plant which ensures complete destruction, having combustion efficiency of 99.999%. Thermal oxidation plant parameter maintained as per design /notified norms to ensure no leakage of HFC-23.
- The operation is through Distributed Control system (DCS) with full interlock logic, which is regularly monitored.
- Leak detection and repair (LDAR) protocol is adopted to curb fugitive emissions of chemicals on the shop floor on an annual basis.

3.6 Additional Learning

The EU noted that a company in the Netherlands produces HCFC-22 and uses internal destruction of its by-produced HFC-23 (thermal incineration). The company is subject to approval, revision of permits and regular inspection procedures by the competent authorities. Most recent inspections (site visit and audit) took place in 2024. One of the issues involved controls on the correct emission data of by-produced HFC23.

Advance

The company reported further as to the Monitoring, Reporting and Verification carried out at the Dordrecht HCFC-22 production plant regarding the different sources of emissions:

Fugitive emissions - an external certified company does fugitive emission measurements on the site according to the prescribed LDAR (Leak Detection and Repair) program by the local environmental authorities. Fugitive emissions are measured, calculated, and reported.

Concentrated HFC-23 streams - HFC-23 is a byproduct of the HCFC-22 production. HFC-23 is separated from the HCFC-22 by distillation. HFC-23 is incinerated in the Thermal Oxidizer, which is the abatement system for all waste gas streams from the HCFC-22 and monomer plants.

This Thermal Oxidizer is more than 99,99 % effective for HFC-23 abatement. Only in cases the TO system or the waste gas feed system fails, or during plant starts and shutdowns[77], there were emissions of this stream in 2022[78]. Emissions are calculated using flow measurements, in line analysers and valve positions.

Clearing emissions of scheduled plant maintenance activities - the amount of the emission is calculated based on volume and pressure of, and composition in, the to-be-cleared equipment.

Emission numbers are based on continuous measurements in our production plants. These numbers are used to define the reported figure in the e-MJV (the Dutch yearly environmental year report).

The HFC-23 emission from the Dordrecht Facility is not a continuous emission.

Emissions can vary considerably over time.

The way of reporting is also audited periodically by authorities for the F-gas regulation.

Advance

[77] Plant start-ups and shutdowns up until the 1st of January 2024 led to situations where the operating conditions of the waste gas feed system were such that these waste gasses could not be fed to the Thermal Oxidizer (e.g., insufficient pressure/flow) and therefore were temporarily emitted.

[78] End of 2023 we have implemented a new air abatement system that further lowers our FOC emissions by 80%, and resolves emissions at times the Thermal oxidizer fails. This means that at present, the emissions of concentrated HFC-23 waste streams (B) have been reduced to zero and the emissions of the diluted HFC-23 waste streams (C) have been further reduced.

ANNEX 1

Information on the possible chemical pathways that could be used in the production of Annex C Group I and Annex F HFCs that may generate HFC-23 as a by-product

This Annex reproduces (with updates to heading references) information contained in section 2 of TEAP's response to decision XXXIV/7, Strengthening institutional processes with respect to information on HFC-23 by-product emissions.[79]

In response to decision XXXIV/7, paragraph a, this section describes information on the possible chemical pathways that could be used in the production of Annex C Group I and Annex F HFCs that may generate HFC-23 as a by-product.

A1.1 Background to HFC-23 by-production

Section 2.3 of the MCTOC 2022 Assessment Report outlined several chemical pathways and processes that can generate HFC-23.

There are several chemical mechanisms that can, by their nature, generate HFC-23 as a by-product in chemical production processes, including:

- *Over- or under-reaction of chemicals* present in the reaction vessel enroute to the intended product, e.g., HFC-23 is an over-fluorination of HCFC-22.
- *Presence of impurities in the feedstocks that are being reacted*, e.g., the chloroform impurity in dichloromethane feedstock, used to produce HFC-32, is hydrofluorinated to HFC-23.
- *Unintended side reactions*, where the feedstock follows a different reaction path than the one that is desired to make the product, e.g., cleavage of carbon–carbon bond in the production of HFC-125 from perchloroethylene, with subsequent hydrofluorination of the resulting mono-carbon molecule to form HFC-23.

For many processes producing fluorinated controlled substances, HFC-23 by-product generation is possible. In the production of HCFC-22, HFC-23 by-product generation cannot be eliminated, with 1–3 wt.% HFC-23 generation being typical. For other processes, very low generation rates are possible; with careful design and operation of the process, HFC-23 by-product generation rate can be minimised to less than 0.1 wt.%, often less than 0.01 wt.%, of production, with emission mitigation reducing the final HFC-23 emission rate further. For many HCFC and HFC production processes, little or no effort has been taken to date to eliminate HFC-23 by-product generation because the "natural" HFC-23 generation rate of the process is so low as to not make it cost-effective. With an effectively operated HFC-23 mitigation step, e.g., thermal oxidation on the process vents containing HFC-23, HFC-23 emission rates can be significantly lower than the HFC-23 by-product generation rates because destruction efficiencies can exceed 99%.

The design intent of most plants is to minimise the generation of by-products to the extent possible within the limits of inherent chemistry and available applied engineering. This is for financial reasons, where most processes typically seek to minimise generation of unwanted by-products to maximise

[79] UNEP, 2023, *Report of the TEAP, Volume 6, Response to decision XXXIV/7, Strengthening Institutional Processes with Respect to Information on HFC-23 By-product Emissions*, September 2023. Section 2, Information on the possible chemical pathways that could be used in the production of Annex C Group I and Annex F HFCs that may generate HFC-23 as a by-product.

desired feedstock to product conversion ratios. Unwanted by-products tend to have a detrimental economic effect because they:

- Consume feedstocks that cannot be (made into and) sold as final product.
- May require additional process steps (and cost) to remove them from final product and/or to mitigate emissions of by-product e.g., thermal oxidation.
- Make final product out of specification in some cases.

In some cases, however, an increase in the rate of production of the desired product at the expense of a higher by-product production rate may be economically attractive.

By-product can be present in gaseous, liquid or solid waste streams and as impurities in products and co-products, from which there is potential for emissions. For example, HFC-23 emissions from HCFC-22 production may occur at several stages: direct emissions of HFC-23 from a vent; HFC-23 degassed to atmosphere during subsequent treatment of the aqueous effluent, possibly off-site; and, to a lesser extent, emissions resulting from HFC-23 present as an impurity in the finished HCFC-22 product and its emission.

A1.2 Information on the chemical pathway used to produce HCFC-22 that generates HFC-23 as a by-product

HFC-23 is primarily generated by the fluorination of chloroform, via the chloroform, HCFC-21, HCFC-22 to HFC-23 pathway in fluorination or hydro-fluorination chemical processes.

The chemical pathway involving the two-step reaction of chloroform ($CHCl_3$) and anhydrous hydrogen fluoride (HF) to produce HCFC-22 ($CHClF_2$) is employed in many plants around the world.

1.	$CHCl_3$	+	HF	→	$CHCl_2F$	+	HCl
	Chloroform		*fluorinated to*		*HCFC-21*		
2.	$CHCl_2F$	+	HF	→	$CHClF_2$	+	HCl
	HCFC-21		*fluorinated to*		*HCFC-22 (product)*		

Ideally the HCFC-22 is removed from the reactor as soon as it is formed. However, in all cases, some HCFC-22 is further fluorinated to HFC-23 before the HCFC-22 can be removed from the reactor.

$CHClF_2$	+	HF	→	CHF_3	+	HCl
HCFC-22		*fluorinated to*		*HFC-23 (by-product or co-product)*		

This process is widely understood to be the main source of global HFC-23 by-product generation[80]. HFC-23 generation[81] rates are typically around 1–3 wt.%, or 10–30 kg of HFC-23 by-product generated per tonne of HCFC-22 and can be as high as 4 wt.%. Operators of HCFC-22 production facilities can then take measures to minimise the emissions of the HFC-23 generated by the process.

[80] The estimated global generation of HFC-23 by-product based on current expert knowledge of production quantities and HFC-23 by-product generation rates by process is around 25 ktonnes per year, with a range of 16–32 ktonnes per year. HFC-23 generated will only be emitted if it is not captured, used as feedstock, or destroyed before it leaves the process, e.g., by incineration.

[81] HFC-23 generation is assumed to mean the total HFC-23 produced by the process, regardless of whether it is later destroyed by a mitigation stage in the same process, it is captured and destroyed at another location, leaves as an impurity in a final product or is emitted by the plant.

Advance

Section A1.5 below estimates the relative generation rates of HFC-23 per tonne of production and global production for chemical pathways that may generate HFC-23 as a by-product, along with an indication of data quality on which to base estimations of HFC-23 generation rates.

A1.3 Information on chemicals pathways used to produce Annex C Group I, other than HCFC-22, and Annex F HFCs that may generate HFC-23 as a by-product

Chemical pathways used to produce Annex C, Group I, substances other than HCFC-22, and Annex F substances can also generate HFC-23 as a by-product, either because:

- They have chloroform present as an impurity in the feedstock, where impurity levels are typically less than 100 ppm (often less than 10 ppm) of chloroform, meaning that less than 0.1 kg (often less than 10 grams) of HFC-23 will be generated per tonne of Annex C, Group I, or Annex F substance.
- They can form either chloroform, HCFC-21 or HCFC-22 in their reaction step, e.g., by the chlorination of dichloromethane ($CH_2Cl_2 + Cl_2 \rightarrow CHCl_3 + HCl$). These species are then hydro-fluorinated to form HFC-23. The chemical pathway that uses dichloromethane as a feedstock to produce HFC-32 generates HFC-23 via this chemical process, estimated at rates less than ~1 kg of HFC-23 per tonne of HFC-32.
- For chemical processes using feedstocks with two or more carbon atoms, such as production of HFC-134a (from trichloroethylene) or HFC-125 (from perchloroethylene), HFC-23 can be formed following the breaking of one of the carbon–carbon bonds. In this case, the quantity of HFC-23 formed is believed to be small, with 0.1 kg, or less, of HFC-23 formed per tonne of product.[82]
- HFC-23 generation is also noted in HCFC-22 plant caustic scrubbers where NaF is present, making the fluorination of HCFC-22 to HFC-23 possible. This is a minor reaction under normal process plant operating conditions, typically increasing HFC-23 in the final HCFC-22 product by at most a few 10s of ppm (i.e., a few 10s of grams) of HFC-23 per tonne of HCFC-22 produced.
- The pyrolysis of HCFC-22 to make tetrafluoroethylene (TFE), which can be used to produce HFC-125, is known to generate small quantities of HFC-23, around 1 kg of HFC-23 per tonne of HCFC-22 consumed.
- The production of hexafluoropropylene (HFP) from HCFC-22, which can be used to make HFC-227ea, is understood to generate small quantities of HFC-23, around 1 kg of HFC-23 per tonne of HCFC-22 consumed. Typically, HFP is co-produced with TFE.
- Disproportionation is understood to occur as a minor reaction in some Annex F production processes (e.g., $2C_2HClF_4$ (HFC-124) $\rightarrow$ C_2H2F_4 (HFC-134a) + $C_2Cl_2F_4$ (CFC-114)). While HFC-23 generation is theoretically feasible, no evidence has been found that indicates that this mechanism leads to HFC-23 generation.

These chemical processes may be present in a range of chemical pathways used to produce Annex C Group I and Annex F HFCs (and other substances not controlled by the Montreal Protocol), meaning that a range of chemical pathways may generate HFC-23 as a by-product.

Some chemical pathways used to produce Annex C Group I and Annex F HFCs have good evidence of HFC-23 generation and its associated rates (e.g., HCFC-22 from chloroform). Other chemical pathways used to produce Annex C Group I and Annex F HFCs have more limited evidence of HFC-

Advance

[82] HFC-23 generation was not found in at least one HFC-152a plant indicating that detectable HFC-23 generation by this route may require a fully halogenated carbon atom when the carbon–carbon bond is broken.

23 generation, although generation is theoretically feasible through any of the above chemical processes (e.g., HFC-32 from dichloromethane, HFC-125 from perchloroethylene, HFC-134a from trichloroethylene). Evidence is limited due to insufficient data, with a lack of emissions reporting and a lack of reference to HFC-23 generation in patents. Nevertheless, HFC-23 generation is theoretically feasible and potentially present in trace amounts. For some chemical pathways, the rate of HFC-23 generation may be so low (practically zero) that HFC-23 would remain undetected in routine analysis.

With these data qualifications in mind, the chemical pathways that could be used to produce Annex C Group I other than HCFC-22 and co-produced HCFC-21 and Annex F HFCs that *may* generate HFC-23 as a by-product are:

- HFC-32 from dichloromethane
- HFC-125 from perchloroethylene, including co-production of HCFC-124 and HCFC-123
- HFC-134a from trichloroethylene, including co-production of HCFC-133a
- HCFC-142b from vinylidene chloride or trichloroethane
- HFC-152a from vinyl chloride
- HFC-143a from trichloroethane
- HFC-227ea from HFP
- HFC-245fa from pentachloropropane

In combination, these chemical pathways used to produce Annex C Group I other than HCFC-22 and Annex F HFCs are currently estimated to generate up to around 1% of total global HFC-23 by-product generation.[83]

Section A1.5 below estimates the relative generation rates of HFC-23 per tonne of production and global production for chemical pathways that may generate HFC-23 as a by-product, along with an indication of data quality on which to base estimations of HFC-23 generation rates.

A1.4 Information on chemicals pathways used to produce substances other than Annex C Group I or Annex F HFCs that may generate HFC-23 as a by-product

Some chemical pathways used to produce substances other than Annex C Group I or Annex F HFCs, which are outside the scope of decision XXXIV/7, are understood to generate HFC-23 by-product. In combination, these chemical pathways are currently estimated to account for around 3–4% of the total global HFC-23 by-product generation. The largest contributor of these chemical pathways to global HFC-23 by-product generation is likely to be the pyrolysis of HCFC-22 to make TFE and HFP, which can be used to produce fluoropolymers. This process is understood to generate small quantities of HFC-23, up to around 1 kg of HFC-23 per tonne of HCFC-22 consumed (0.1 wt.%).[84] Other chemical pathways where HFC-23 by-product generation is theoretically feasible include those used to produce CFCs, namely CFC-113 from perchloroethylene and CFC-114 from perchloroethylene.

The production routes of other fluorochemicals outside of the scope of the decision have similarities to the chemical processes used to produce Annex C Group I and Annex F HFCs and hence could conceivably generate HFC-23 by similar mechanisms. The HFC-23 generation rate could be expected to be similar to other chemical pathways used to produce Annex F HFCs (typically less than 0.01 wt.%). However, there is currently insufficient data available on production volumes and HFC-23

[83] There was only a limited amount of information available on likely HFC-23 generation rates from these processes at the time of writing this report so there is a reasonable degree of uncertainty for estimates of current global HFC-23 generation rates from these chemical pathways and processes.

[84] See MCTOC 2022 Assessment Report, section 2.3.2, Emissions of HFC-23 and PFC-c-318 from the manufacturing process used to produce tetrafluoroethylene and hexafluoropropylene from HCFC-22 for a discussion of HFC-23 generation.

generation rates in these processes to make anything other than rough estimates of possible HFC-23 generation for these processes.

Another potential chemical pathway is the fluorination of polyethylene by fluorine gas. While there is no direct published evidence, HFC-23 generation could be considered theoretically feasible in this process, particularly as it has been reported that short-chain perfluorinated carboxylic acids can be formed depending on conditions.[85] This chemical pathway is not considered further in this report.

A1.5 Estimated global HFC-23 generation for chemical pathways that may generate HFC-23 as a by-product

Section 3[86] responds to decision XXXIV/7, paragraph b, which, among other things, requests the compilation of information on the amount of HFC-23 generation from facilities that manufacture Annex C, Group I, or Annex F substances, the reporting of which is required under Article 7 of the Montreal Protocol.

For additional context and understanding of the potential relative contributions to HFC-23 by-product generation, this section provides indicative estimations of relative global HFC-23 generation by relevant chemical pathways. These estimations can be made by considering the various processes identified to generate HFC-23 by-product (sections A1.1 to A1.4), known chemical pathways and their global production rates (either reported to the Ozone Secretariat or estimated), the data compiled in Section 3, and estimated HFC-23 generation rates based on available data and/or expert opinion. MCTOC's assessment based on available data and expert opinion is shown in the matrix representation in Figure A1.1 and in Tables A1.1 and A1.2.

Figure A1.1 and Table A1.1 present estimations based on sufficient available data on HFC-23 by-product generation, even if the data are limited. Estimates include chemical pathways used to produce Annex C Group I, Annex F HFCs, and substances other than Annex C Group I and Annex F HFCs where HFC-23 by-product generation is more than around 10 tonnes per year globally.

Table A1.2 presents order of magnitude estimations of HFC-23 by-product generation for chemical pathways that can be used to produce controlled substances, including Annex C Group I, Annex F HFCs, and CFCs, where insufficient HFC-23 generation data are available. These estimates are based on MCTOC expert opinion.

It should be noted that there is currently a lot of uncertainty, including in the matrix representation in Figure A1.1, as there are little or no specific HFC-23 generation data available for many of the chemical pathways. What little HFC-23 generation data are available can be found in, for example:

- Patents, which may not reflect actual operating experience at scale or report anything other than an indication of the presence of HFC-23
- Reported HFC-23 emissions data, for which there typically is no indication of associated abatement or mitigation of any HFC-23 generation, or
- Occasional plant HFC-23 generation data, which may not be representative of the true global mean HFC-23 generation rate for the chemical pathway.

[85] See, for example, Amy A. Rand and Scott A. Mabury, Perfluorinated Carboxylic Acids in Directly Fluorinated High-Density Polyethylene Material, *Environmental Science & Technology,* 2011, **45**(19), 8053–8059. DOI: 10.1021/es1043968.

[86] UNEP, 2023, *Report of the TEAP, Volume 6, Response to decision XXXIV/7, Strengthening Institutional Processes with Respect to Information on HFC-23 By-product Emissions*, September 2023. Section 3.

Advance

The process that has the most complete set of HFC-23 generation data[87], HCFC-22 production from chloroform, is also understood to be the major source of HFC-23 generation.

A more refined estimate of HFC-23 generation for chemical pathways would be possible through better data availability[88], which could alter the matrix in Figure A1.1 and Tables A1.1 and A1.2, and the current conclusions.

Advance

[87] The HFC-23 generation data from HCFC-22 production are available for numerous plants (e.g., through their UNFCCC CDM reports (https://cdm.unfccc.int/Projects/projsearch.html) and other national reporting programs) and has been widely discussed for many years leading to a broadly consensual view on the range and mean HFC-23 generation rates (Section 3.1). Annual HCFC-22 production has also been reported under the Montreal Protocol for many years (Ozone.unep.org).

[88] As plants producing controlled substances are typically covered by national environmental regulations and will seek to optimise their economic viability, it is likely that more data are gathered on HFC-23 generation than is currently available.

Figure A1.1 Matrix of estimated relative global HFC-23 generation for currently identified chemical pathways that may generate HFC-23 as a by-product (> ~10 tonnes per year globally), predicted based on reported global production and estimated mean HFC-23 generation rate

		Global production				
		<1000 tonnes of product per year	1,000–10,000 tonnes of product per year	10,000–100,000 tonnes of product per year	100,000–1 million tonnes of product per year	>1 million tonnes of product per year
HFC-23 mean generation rate from production	1–10 wt.% 10–100 kg of HFC-23 generation per tonne of production					**1**
	0.1–1 wt.% 1–10 kg of HFC-23 generation per tonne of production					
	0.01–0.1 wt.% 0.1–1 kg of HFC-23 generation per tonne of production				**2, A, B**	
	0–0.01 wt.% 0–100 grams of HFC-23 generation per tonne of production	<100 kg per year			**3**	

Note: The numbers in Figure A1.1 matrix refer to the reference numbers in Table A1.1 below

	Less than 100 tonnes of HFC-23 generated globally per year
	More than 10,000 tonnes of HFC-23 generated per year

Table A1.1 Reference table for the matrix of chemical pathways, for which generation of HFC-23 by-product (> ~10 tonnes per year globally) is estimated in Figure A1.1

Reference number	Substance produced	Chemical pathway	Estimated global production tonnage band for each chemical pathway (tonnes per year)	Estimated likely mean HFC-23 generation per tonne of process production globally[89] (weight %)	Availability of HFC-23 generation data
Pathways directly to controlled substances					
1	HCFC-22	Chloroform to HCFC-22, including co-production of HFC-23 and HCFC-21	>1 million	1–10[a]	Good
2	HFC-32	Dichloromethane to HFC-32	100,000–1 million	0.01–0.1[b]	Poor
3	HFC-125	Perchloroethylene to HFC-125, including co-production of HCFC-124 and HCFC-123	100,000–1 million	0.001–0.01[c]	Very poor
Pathways not directly to controlled substances					
A	TFE	HCFC-22 to TFE	100,000–1 million	0.01–0.1[d]	Poor
B	HFP	HCFC-22 to HFP	100,000–1 million	0.01–0.1[d]	Very poor

Supporting references and comments

a. MCTOC 2022Assessment Report, page 40; significant quantity of plant HFC-23 generation data, e.g., UNFCCC CDM projects (some dated).

b. MCTOC 2022 Assessment Report, page 44, US EPA, 2021, Stratospheric Protection Division, Office of Air and Radiation (OAR) Report, *Facilities with HFC-23 Emission*, April 2021[90]; limited quantity of actual plant HFC-23 generation and reported HFC-23 emission data.

c. TEAP 2023 Progress Report, page 41, US EPA, 2021, Stratospheric Protection Division, Office of Air and Radiation (OAR) Report, *Facilities with HFC-23 Emission*, April 2021; limited plant data. Annual global HFC-23 generation by this chemical pathway could credibly be below 10 tonnes per year.

d. MCTOC 2022 Assessment Report, page 41; and example environmental permit of TFE production plant[91].

[89] This is based on reported emissions or analysis from operating plants and or sites, it should be noted that for many pathways the quantity and quality of available data are limited and are subject to confirmation through further acquisition of data.

[90] http://www.regulations.gov/document/EPA-HQ-OAR-2021-0044-0046.

[91] EPR/BU5453IY/V004.

Advance

A1.5.1 Order of magnitude estimation of HFC-23 by-product generation for chemical pathways to produce controlled substances where insufficient HFC-23 generation data are available

Table A1.2 presents estimates based on expert opinion of annual HFC-23 by-product generation for chemical pathways used to produce Annex C Group I, Annex F HFCs, and CFCs (outside the scope of this decision), where there is greater than 10,000 tonnes per year of global production and where little or no specific HFC-23 generation data are available.

These estimates have been included to support understanding of the likely order of magnitude of HFC-23 by-product generation from these chemical pathways.

Chemical pathways to produce HCFC-142b, HFC-143a, HFC-152a, HFC-227ea, HFC-245fa, CFC-113, and CFC-114, with annual production of greater than 10,000 tonnes per year, are each considered likely to have HFC-23 by-product generation of less than 1 tonne per year globally. The chemical pathway to produce HFC-134a from trichloroethylene, with annual production 100,000–1 million tonnes per year, is considered likely to have HFC-23 by-product generation of less than 10 tonnes per year globally.

Chemical pathways, with annual production of controlled substances of less than 10,000 tonnes per year each, are considered likely to have insignificant total global HFC-23 by-product generation and are not considered further in this report.

HCFC-21 is also produced for feedstock use at less than 10,000 tonnes per year; however, it is usually produced as a by-product from HCFC-22 production and any over fluorination to form HFC-23 can be considered associated with the production of HCFC-22 (the reaction pathway is HCFC-21 to HCFC-22 to HFC-23). If HCFC-21 is produced on dedicated HCFC-21 production plants, without HCFC-22 co-production, the magnitude of the HFC-23 generation rate would be expected to be lower.

It should also be noted that, when required as a product, HFC-23 is neither destroyed nor vented; rather, it is collected for use as a feedstock or for emissive uses.

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Table A1.2 Table of expert opinion estimates of annual global HFC-23 generation for chemicals pathways producing >10,000 tonnes per year globally of controlled substances where little or no HFC-23 generation data are currently available

Controlled substance produced	Chemical pathway	Estimated global production tonnage band for each chemical pathway (tonnes per year)	Availability of HFC-23 generation data[92]	Estimate of annual HFC-23 generation (tonnes per year)
HCFC-142b	Vinylidene chloride/Trichloroethane	100,000–1 million	Insufficient data available.	<1
HFC-134a	Trichloroethylene to HFC-134a, including co-production of HCFC-133a	100,000–1 million	Limited evidence of trace HFC-23 being generated[a]	<10
HFC-143a	Trichloroethane	100,000–1 million	Insufficient data available. Lack of emission reporting and patent reference to HFC-23 generation could indicate only trace HFC-23 being generated	<1
CFC-113	Perchloroethylene to CFC-113	100,000–1 million		<1
HFC-152a	Vinyl chloride to HFC-152a	10,000–100,000	Insufficient data available. Lack of emission reporting and patent reference to HFC-23 generation could indicate only trace HFC-23 being generated, coupled with lower global production.	<1
HFC-227ea	HFP to HFC-227ea[93]	10,000–100,000		<1
HFC-245fa	Pentachloropropane	10,000–100,000		<1
CFC-114	Perchloroethylene to CFC-114	10,000–100,000		<1

Supporting references and comments

a. Limited plant data indicate very low levels of HFC-23 detected[94], with similar reactor chemistry to HFC-125; HFC-23 generation is likely to be small because emissions are not typically reported.

[92] This is based on reported emissions or analysis, or lack thereof, from operating plants and or sites. It should be noted that for many pathways the quantity of data is limited and subject to confirmation through further acquisition of data if the data become available. For some of these chemical pathways, the rate of HFC-23 generation may be so low (practically zero) as to be undetected in routine analysis.

[93] Note this pathway is only the HFP to HFC-227ea element; the chloroform to HCFC-22 and HCFC-22 to HFP elements are included in Table A1.1.

[94] One unpublished example, which analysed the components from the degassing tower after the HFC-134a reactors, found ~10ppm HFC-23, confirming HFC-23 generation in trace quantities.

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A1.5.2 HFC-23 by-production due to the electrochemical production of fluorocarbons

It has been reported that electrochemical production of fluorocarbons can produce HFC-23 by-product[95]. A site undertaking the electrochemical production of fluorocarbons has reported annual HFC-23 emissions in excess of 40 tonnes (Section 3[96]). Therefore, it could be expected that because the electrochemical production of fluorochemicals generates more than 10 tonnes per year of HFC-23 by-product, these chemical pathways should be included in the matrix or the tables. However, as information on the substances produced, their HFC-23 generation rates, and the estimated global production tonnages are not generally available to MCTOC, HFC-23 by-product generation during electrochemical production of fluorocarbons is not included in the matrix or tables.

A1.5.3 HFC-23 generation rates during the production of HFOs

HFOs are not Annex C Group I or Annex F HFCs, and, as also for TFE and HFP, are outside the scope of decision XXXIX/7.

HFO production is not included in Tables A1.1 and A1.2 because insufficient data are currently available. However, it is reported that some chemical pathways and processes used to produce HFO-1234yf go through HCFC-22, HFP and/or TFE intermediates[97]. If the quantity of HCFC-22 is reported as feedstock to the Ozone Secretariat, then its associated HFC-23 by-product generation would be accounted for in the respective feedstock related HFC-23 generation. If the HCFC-22 is not reported as feedstock (unlikely), then additional HFC-23 by-product generation not currently accounted for may be taking place.

A1.5.4 HFC-23 generation rates through fluoropolymer destruction

There is the possibility that HFC-23 can be generated during the destruction of fluoropolymers[98]. There is currently no data relating to HFC-23 generation rates from real-life destruction of fluoropolymers.

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[95] MCTOC 2022 Assessment Report, page 45.

[96] UNEP, 2023, *Report of the TEAP, Volume 6, Response to decision XXXIV/7, Strengthening Institutional Processes with Respect to Information on HFC-23 By-product Emissions*, September 2023. Section 3.

[97] MCTOC 2022 Assessment Report, page 38.

[98] Huber, S., Moe, M.K., Schmidbauer, N., Hansen, G.H., Herzke, D., *Emissions from incineration of fluoropolymer materials. A literature survey*, The Norwegian Pollution Control Authority (SFT), NILU OR 12/2009, 2009, https://www.nilu.com/publication/24739/. Accessed August 2023.

ANNEX 2

Best practices available to control emissions of HFC-23 by-product (as in TEAP Response to Decision XXXIV/7[99])

Best practices available to control emissions of HFC-23 by-product are consistent with those used to control other emissions associated with chemical manufacturing.

These include optimising plant design, equipment, operation, maintenance; instrumentation and monitoring of process and emissions; training and instruction for plant operators; periodic mass balancing; technologies for destruction (i.e., thermal oxidation) or for separation and chemical transformation to treat unwanted co-products or by-products and abate their emissions; and regulatory controls to provide the economic framework to ensure any or all of the above emissions mitigation measures are implemented by operators, and to require emissions and other reporting.

Article 2J requires HFC-23 emissions generated in production facilities that manufacture Annex C, Group I, or Annex F substances to be destroyed to the extent practicable using technology approved by the Parties. Of the best practices available to control emissions, thermal oxidation is used as an end-of-pipe process that destroys unwanted by-products to environmentally acceptable substances. When a process includes an effectively operated HFC-23 mitigation step, e.g., thermal oxidation on the process vents containing HFC-23, emission rates of HFC-23 can be significantly lower than the HFC-23 generation rates because destruction efficiencies can exceed 99%. The capital cost is estimated as ~US$1.25–3.5 million, with annual operating costs ~US$300,000–600,000.

MCTOC elaborated generic best practices available to control emissions in its recent 2022 Assessment Report, Section 2.5, on production emissions and their mitigation, which was reproduced in its recent response to decision XXXIV/7, paragraph c, and is reproduced again below.

A2.1 Production emissions and their mitigation

An emission is usually considered to be the release of a substance into the environment; although often used to describe gas releases to the atmosphere, they can also include substances released in solids or liquids that later transition to the atmosphere. For example, the HFC-23 emission from an HCFC-22 process may include both direct emissions of HFC-23 from a vent and HFC-23 degassed to atmosphere during subsequent treatment of the aqueous effluent.

In some processes, substances can be dissolved or entrained in some of the co-products and can then be released to the environment in the location where these co-products are subsequently stored and used, which is often remote from the plant that produced them. For example, HFC-23 can be dissolved or entrained in the co-produced hydrochloric acid on an HCFC-22 process. The dissolved or entrained HFC-23 is then degassed to atmosphere from locations where the hydrochloric acid is subsequently stored and used. This can result in a wide dispersal of the eventual HFC-23 transitions to atmosphere and an apparent proliferation of secondary HFC-23 emission sources. It should be noted that this is not additional by-production of HFC-23 from either the HCFC-22 process or at the point of emission. The quantity of HFC-23 released in these dispersed emissions can vary widely as the quantity involved is dependent on several factors involved in the design and operation of the producing plant. These dispersed emissions are expected to account for <1% by weight of the total HFC-23 by-production of the HCFC-22 process. These dispersed emissions are typically unmitigated at point of release.

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[99] UNEP, 2023, *Report of the TEAP, Volume 6, Response to decision XXXIV/7, Strengthening Institutional Processes with Respect to Information on HFC-23 By-product Emissions*, September 2023. Section 4.

Emissions can be of products, co-products, intermediates, feedstock, or by-products; which of these are being emitted will have an important bearing on how the operation mitigates those emissions.

A2.2 Emission of products, co-products, intermediates, and feedstocks

Emissions of products, co-products, intermediates, and feedstocks from processes are economically undesirable and the operators of the process will seek to minimise them. To achieve this the process will usually be designed, operated, monitored, and controlled to optimise feedstock to product ratios, and hence minimise product, co-product, intermediate and feedstock emissions within the limits of the plant design capability.

Most processes will employ a range of elements of good practice for minimising emissions of feedstocks, intermediates, and products, such as:

- Operating instructions documenting how to consistently achieve the desired optimum operation
- Training
- Instrumentation to allow suitable monitoring and control of the process
- Routine sampling and analysis of raw material, product and solid and liquid effluent and vent streams
- Routinely recording, trending, and reviewing relative feedstock consumption and product production ratios
- Periodic plant mass balancing
- Plant tours
- Maintenance procedures including routine leak checking
- Consideration of inherent emissions when selecting equipment, e.g., seal-less pumps
- Consideration of the materials of construction.

The operator may even, in some cases, alter the physical design of the process to reduce these emissions if there is a suitable case to do so.

A2.3 Emissions of unwanted by-products

Emissions of unwanted by-products, and to a lesser extent low value co-products, is a different consideration. For financial reasons, a process will typically seek to minimise the formation of unwanted by-products because by doing so it will typically maximise its desired product to feedstock conversion ratios. Nevertheless, in some cases an increase in the rate of production of the desired product at the expense of a higher by-product production rate may be economically attractive. There would usually be a need to include additional equipment (such as destruction or separation and chemical transformation technologies), with further operating and maintenance costs to the process to mitigate these unwanted by-product emissions. However, the lack of a clear environmental, safety or economic drivers has often meant that, once produced, these unwanted by-products are emitted unabated.

If there are no financial incentives, regulatory controls may be needed to ensure that the emissions of unwanted by-products produced by the process are minimised. Various techniques are possible to treat unwanted by-products to minimise their emission. These techniques are typically end-of-pipe processes that destroy or convert the unwanted by-products to environmentally acceptable substances; e.g., conversion of the HCl and HF to hydrochloric and hydrofluoric acids or salts such as NaF and NaCl using aqueous scrubbing systems; or the thermal oxidation of HCFCs to water, CO_2, HCl and

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HF and the subsequent conversion of the HCl and HF to salts such as CaF_2 and $CaCl_2$ or in some cases the absorption of certain organic species on an absorbent (e.g., activated carbon) prior to appropriate disposal or regeneration of the absorbent.

A2.4 Emissions monitoring

The determination of emission rates by process operators can be complex often requiring the monitoring of the flow and composition of numerous process streams. The physical and chemical characteristics of these streams may also present significant challenges to achieve a sufficiently reliable and accurate set of data. In additional it is difficult to obtain a complete coverage of all emission as, for example, fugitive (unintended) emission points (e.g., leaks from pipework, flanges or fittings) are not suitable for continuous measurement and usually must be estimated/determined by mass balancing the flows into and out of the process.

The ability of processes to monitor, and the accuracy of the determination of, their substance emissions rates will vary. Some modern suitably designed, operated and highly instrumented processes may have continuous flow and frequent composition monitoring of all relevant flows into and out of the plant and be able to consistently balance the inputs and outputs, including emissions, from the plant to a reasonably high degree of accuracy, less well instrumented and monitored plants, maybe only covering the major raw material, product and vent steams, are still likely to mass balance their process but will only be able to do so to a lower accuracy and will be less able to determine the chemical species and route of any emissions.

Factors that affect the amount of instrumentation and the accuracy of the determination of emissions are numerous and include, for example:

- The age and design of the plant
- The presence (where in the process, for how long, with which other substances and in what physical state) of the chemical species being emitted
- The suitability of the measurement technique for the parameter to be measured
- The degree of accuracy and frequency of measurements of the flows and compositions of the various feedstocks, products, and emission points
- The number of possible (normal, emergency and fugitive) emission points to be monitored
- The percentage of the emission points monitored
- The regulatory requirements to measure and document emissions
- The perceived economic value and hence resources expended by the operator to estimate, control, minimise, and mitigate emissions.

In general, the more resource and importance an operator places on determining emissions and the higher the completeness, reliability and accuracy of the data obtained from the plant, the more accurate the mass balance and hence the more accurate the determination of the emissions.

A2.5 Emission reporting

Many national regulations require the operators of chemical processes to report the level of emissions from the production of a range of substances including many controlled substances. Many of these reports are publicly available although it is often difficult to derive an accurate emission factor as a percentage of the product produced as typically only incomplete data on production rates is publicly available.

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There is also a requirement to report a basket of HFCs to the UNFCCC[100]; these emissions cover a different scope and often a different calculation methodology to the paragraph above as they include an estimation of emissions whilst in use and at end of life.

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[100] For example, UNFCCC, National Inventory Submissions 2021 | UNFCCC

ANNEX 3

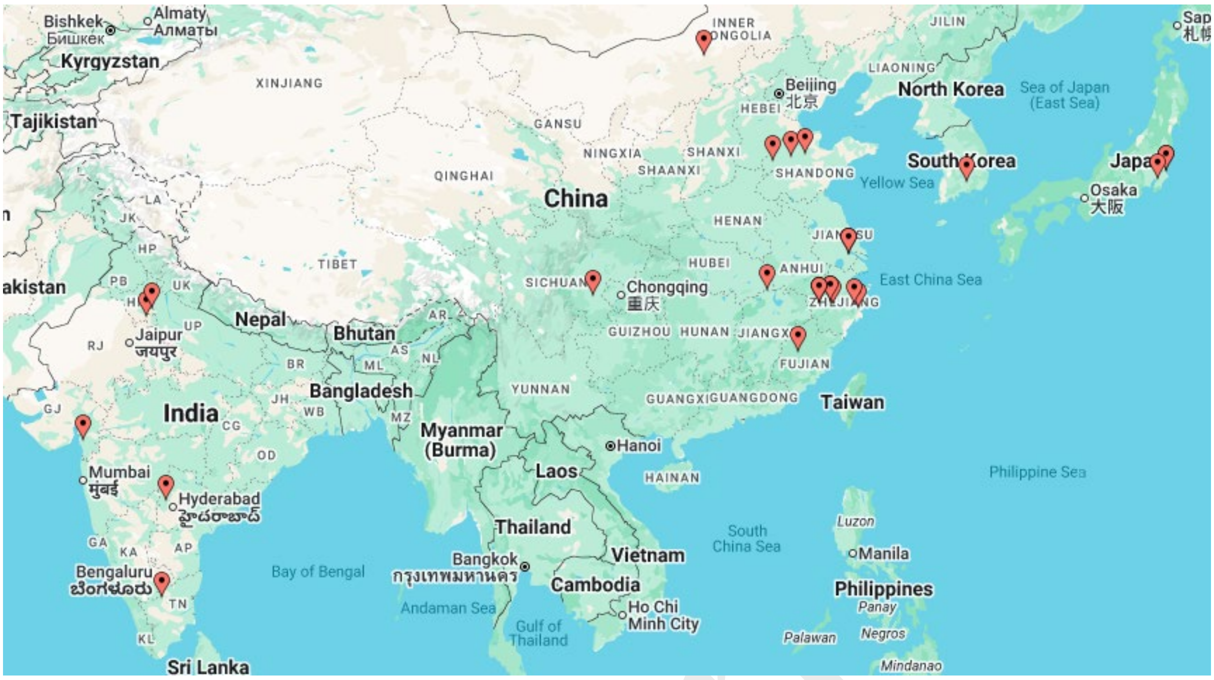
Estimated current and recent historical locations of HCFC-22 production facilities[101]

Americas

Europe and the Russian Federation

[101] Current and recent historical locations of HCFC-22 production facilities are based upon previous reports from the Clean Development Mechanism of UNFCCC, published addresses of manufacturing facilities, and other public sources.

Asia


Bishkek
Бишкек
Almaty
Алматы
Kyrgyzstan
Tajikistan
XINJIANG
GANSU
QINGHAI
NINGXIA
SHANXI
SHAANXI
INNER
MONGOLIA
JILIN
LIAONING
Beijing
北京
HEBEI
North Korea
Sea of Japan
(East Sea)
South Korea
Yellow Sea
SHANDONG
China
Osaka
大阪
HENAN
JIANGSU
HUBEI
ANHUI
East China Sea
SICHUAN
Chongqing
重庆
ZHEJIANG
GUIZHOU
HUNAN
JIANGXI
FUJIAN
TIBET
Nepal
Bhutan
Bangladesh
YUNNAN
GUANGXI
GUANGDONG
Taiwan
Jaipur
जयपुर
India
Myanmar
(Burma)
Hanoi
Laos
HAINAN
Philippine Sea
Mumbai
मुंबई
Hyderabad
హైదరాబాద్
Thailand
South
China Sea
Luzon
Bay of Bengal
Bangkok
Vietnam
Manila
Bengaluru
ಬೆಂಗಳೂರು
Cambodia
Philippines
Andaman Sea
Ho Chi
Minh City
Gulf of
Thailand
Palawan
Negros
Mindanao
Sri Lanka