Market Characterization of the U.S. Semiconductor Industry

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1. Summary

Semiconductor devices are used to provide logic and memory functions in many electronic appliances as well as social infrastructure (e.g., cellphones, computers, data servers) that support everyday life.

Semiconductor manufacture uses three hydrofluorocarbons (HFCs), HFC-23 (CHF_3), HFC-32 (CH_2F_2), and HFC-41 (CH_3F), primarily in etching processes, but also minimally in chemical vapor deposition (CVD) chamber cleaning processes. HFC use in semiconductor manufacturing began in the mid-1980s, along with use of other fluorinated greenhouse gases (GHGs) such as perfluorocarbons and sulfur hexafluoride (EPA 2020).

In 2019, an estimated 52 metric tons (MT) of HFC-23, 5.4 MT of HFC-32, and 3.4 MT of HFC-41 were used in semiconductor fabrication facilities in the United States. The use of HFCs in semiconductor manufacture is expected to continue as HFCs have physical properties that make them well suited for semiconductor manufacturing.

In this analysis, HFC use is projected to grow at the rate observed between 2011 and 2019 (SIA 2021). In 2025, approximately 89 MT of HFC-23, 9.3 MT of HFC-32, and 7.1 MT of HFC-41 is expected to be used in semiconductor manufacturing in the United States.

2. Introduction

Semiconductor devices are critical to the functioning of electronic equipment. They are used to provide logic and memory functions in many electronic appliances as well as social infrastructure (e.g., cellphones, computers, data servers) that support everyday life.

Semiconductor manufacturers use a variety of high-global-warming-potential (GWP) fluorinated gases, including hydrofluorocarbons (HFCs), in two critical processes: to create intricate circuitry patterns upon silicon wafers (etching, also known as plasma etching) and to clean chemical vapor deposition (CVD) chambers (EPA 2020).

Etching is a process type that uses plasma-generated fluorine atoms and other reactive fluorine-containing fragments that chemically react with exposed thin-films (e.g., dielectric, metals) or substrate (e.g., silicon) to selectively remove portions of material. CVD chamber cleaning is a process type in which chambers used for depositing thin films are cleaned periodically using plasma-generated fluorine atoms and other reactive fluorine-containing fragments. Depending on the complexity of the product, the manufacturing process may require upwards of 100 steps utilizing high-GWP gases (EPA 2020). HFC-23 (CHF_3) is the primary HFC used in the manufacturing process, along with HFC-32 (CH_2F_2) and HFC-41 (CH_3F) (EPA 2020).

The remainder of this report characterizes HFC use by the U.S. semiconductor industry, including key market players and historical and current use of HFCs and other high GWP gases in the semiconductor industry.

3. Market Characterization

This section provides an overview of the semiconductor market, as well as the current market segments and key manufacturers.

3.1. Overview of Semiconductor Devices

Since the 1990s, the U.S. semiconductor industry has accounted for a substantial share of global semiconductor production (SIA 2020b). Semiconductors can be classified into four major product groups, primarily based on their function. Some semiconductors have broad functionality, while others are designed for specific use.

- **Microprocessors and logic devices** are used for the interchange and manipulation of data in computers, communication devices, and consumer electronics (CRS 2020). Microprocessors and logic boards account for 42% of total semiconductor sales worldwide (SIA 2020a).
- **Memory devices** are used to store information. This segment includes dynamic random-access memory (RAM or DRAM) that stores temporary bits of information and is found in smartphones, computers, and flash drives. Memory devices accounted for 25% of global semiconductor sales (SIA 2020a).
- **Analog devices** are used to translate analog signals, such as light, touch, and voice, into digital signals. For example, they are used to convert the analog sound of musical performances into a digital recording stored online or on a compact disc (CRS 2020). Analog devices account for 13% of global semiconductor sales.
- **Optoelectronics, sensors, and discrete** (commonly referred to as O-S-D). Optoelectronics and sensors are used for generating or sensing light while discrete are designed to perform a single electrical function (SIA 2020a). O-S-D account for 20% of total semiconductor sales worldwide.

The semiconductor industry uses a variety of fluorinated gases during manufacturing, including perfluorocarbons (e.g., CF_4, C_2F_6, C_3F_8, and C_4F_8), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), HFCs, and fluorinated heat transfer fluids (EPA 2020).[1] HFCs are used in two main stems of the semiconductor manufacture process: etching / wafer cleaning (the primary use of HFCs), but also in CVD chamber cleaning. The etching process uses plasma-generated fluorine atoms and other reactive fluorine-containing fragments, including HFCs, which chemically react with exposed thin-films or substrates to selectively remove the desired proportions of the material and make the desired etching pattern (IPCC 2019). This includes production processes using fluorinated GHG reagents to clean wafers.

Deposition is a vital step in the fabrication of a variety of electronic devices. During deposition, layers of dielectric, barrier, or electrically conductive films are deposited or grown on a wafer or other substrate. CVD enables the deposition of dielectric or metal films. During the CVD process, gases that contain atoms of the material to be deposited react on the wafer surface to form a thin film of solid material (EPA 2010). These deposition tool chambers are cleaned periodically using fluorinated and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma or by thermal dissociation, which etch away residual material from chamber walls, electrodes, and chamber hardware, maintaining the effectiveness of the tools.

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[1] Perfluorocarbons, sulfur hexafluoride, nitrogen trifluoride, HFC-23 account for 62.5 percent, 16.6 percent, 12.5 percent, and 8.3 percent of GWP-weighted emissions, respectively (EPA 2020).

Emissions from both etching and chamber cleaning processes consist of (1) a fraction of each fluorinated GHG that is fed into the process ("input gas") that is not broken down (or is reformed) during the process, and (2) by-product fluorinated GHGs that are formed during the process from the input gas(es). The fraction of the input gas that survives, as well as the identity and quantity of the by-product fluorinated GHGs that are formed, vary depending on the input gas, process, and the size of the wafer on which the semiconductor devices are manufactured.[2] Certain fabrication facilities (fabs) within the United States have implemented a variety of emissions control technologies that significantly reduce emissions of HFCs and other fluorinated GHGs during semiconductor manufacturing.

The physical and chemical characteristics of the single-carbon HFCs make them well suited for use in semiconductor manufacturing processes. Specific HFC compounds are employed in precise quantities and under carefully controlled process conditions to achieve the desired results (e.g., etching a certain type of feature on a semiconductor device). Because HFCs are used only during the manufacture of semiconductors, the finished product does not contain HFCs.

3.2. Purification

The semiconductor supply chain is complex and involves multiple players for the supply of HFC gases. To minimize risk and ensure security in supply, manufacturers source raw materials from a diverse portfolio of suppliers. The raw HFC material is produced at a low grade of around 95-97 percent purity at 30,000 – 50,000 ppm impurities (SIA 2021). This raw product is then passed downstream to a number of purifiers. The HFC must be purified to 99.9999% or 1-10 ppm impurities before it can be used by semiconductor manufacturers (Electronic Fluorocarbons 2021). This refining process could take up to one year and necessarily results in losses of HFCs during the purification process. One refiner estimates that 1.06 kilograms of raw HFCs are required to produce 1.0 kilograms of semiconductor grade HFC (Adams 2021), which represents 5.7 percent in losses. Loss rates above 10 percent were estimated by one producer of HFCs (Arkema 2021b).

3.3. Major Manufacturers

A number of U.S.-headquartered or foreign-owned semiconductor companies currently operate over 70 fabs in the United States (SIA 2020b, CRS 2020b). The manufacturing output has remained stable for many years (SIA 2020b). Table 1 lists some of the major manufacturers of semiconductors in the U.S. Semiconductor fabs are classified as either 300-millimeter (mm) diameter wafer production facilities or 200-mm diameter wafer production facilities (CRS 2020). Currently, there are more 200-mm fabs than 300-mm fabs within the United States (WFF 2020).

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[2] For this reason, most methods for calculating emissions from semiconductor manufacturing multiply the consumption of the input gas by measured or default input-gas and by-product-gas emission factors that vary by input gas, process type or subtype, and wafer size. This includes the calculation method specified for semiconductor manufacturers in the Greenhouse Gas Reporting Program (GHGRP).

Table 1. Some Major Manufactures of Semiconductors in the United States[a]

Company	Number of Fabs	Products
GlobalFoundries	3	Foundry/Dedicated
Intel Corporation	8	Logic/Microprocessor Unit
Micron Technology	4	Memory/Flash/DRAM
Samsung	2	Foundry/IDM
Texas Instruments	2	Analog/Linear

Source: CSR 2020

[a] The companies in this table do not represent an exhaustive list of all semiconductor manufacturing companies within the United States.

HFC producers, including Arkema (Arkema 2021a), Chemours (Semi 2021), Air Liquide (EPW 2020a)[3], and Iofina Chemicals (EPW 2020b), supply some semiconductor manufacturers with HFC compounds (i.e., HFC-23, HFC-32, and HFC-41). Further research would need to be conducted to identify all HFC suppliers to semiconductor manufacturers.

4. Subsector Background and Use

4.1. Current Gases Used in Semiconductor Production

The etching and CVD chamber cleaning processes have both historically utilized HFCs and other fluorinated gases. Table 2 summarizes the environmental characteristics, including ozone depletion potential (ODP) and global warming potential (GWP), for HFCs used in semiconductor production.

Table 2. Environmental Characteristics of HFCs used in Semiconductor Production

Production Gas	ODP[a]	GWP[a]
HFC-23	0	14,800
HFC-32	0	675
HFC-41	0	92

Note: GWPs are aligned with the exchange values used in the AIM act.

[a] Ozone Secretariat

4.2. Method for Estimating HFC Use

HFC use by the semiconductor industry was estimated using data from EPA's Greenhouse Gas Reporting Program (GHGRP). Fabs are required to report their emissions of fluorinated gases and nitrous oxide, as well as the extent to which they abate or control these emissions, under subpart I of the GHGRP.[4] Specifically, fabs report their emissions of each fluorinated GHG and nitrous oxide, indicate whether or not emissions of specific fluorinated GHGs or nitrous oxide from specific processes are abated, and report their fab-wide destruction and removal efficiency (DRE), which is calculated as 1 minus the ratio of controlled, GWP-weighted emissions of

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[3] According to the GHGRP (2011-2019), Air Liquide indicated importing and exporting HFCs. Available at: https://www.epa.gov/ghgreporting/list-companies-reported-hfc-supply.

[4] GHGRP requires fabs that calculate emissions of 25,000 metric tons (MT) or more of carbon dioxide equivalent (CO_2 eq) per year in the United States to report emissions annually. A small percentage of fabs ("non-reporters") are not required to report emissions to GHGRP as these fabs do not meet the 25,000 MT threshold. Emissions data reported under subpart I are not considered to be confidential business information.

nitrous oxide and all fluorinated GHGs to hypothetical uncontrolled, GWP-weighted emissions of nitrous oxide and all fluorinated GHGs.

Fabs that report a fab-wide DRE to the GHGRP are referred to as “abated fabs” for the purpose of this analysis. Fabs that do not implement abatement technology are referred to as “unabated fabs.” In addition, there are at least ten fabs that do not report under the GHGRP as they do not meet the reporting threshold (i.e., non-reporters).

Historical HFC use in semiconductor manufacturing was estimated using emissions and abatement data from the GHGRP and production capacity information (silicon area) from the World Fab Forecast (WFF). (The WFF data is used to estimate HFC use by fabs not reporting to GHGRP.)

The sum of HFC use across the three fab categories described above (i.e., abated fabs, unabated fabs, and non-reporting fabs) is the estimated overall HFC use of the semiconductor industry. Historical estimates for each fab category were calculated for 2013 and 2017 to 2019. Historical estimates for 2015 to 2016 were interpolated based on 2013 and 2017 data.

Estimates of HFC use for 2013 were calculated using GHGRP data in an approach similar to that described below for calculating the estimates of HFC use for 2017 to 2019.

Estimates of HFC use for 2017-19 were calculated as follows. HFC use estimates for **unabated fabs** were calculated using reported GHGRP emissions data and default emission factors for subpart I. Because HFCs are generated as by-products as well as used as input gases, both input gas emission factors and by-product gas emission factors were factored into this calculation.[5] Following the calculation, the estimated consumption of each HFC was divided by the reported emissions of each HFC to develop a “consumption factor” for each wafer size. This consumption factor was used to estimate HFC consumption by abated fabs, as described further below.

To estimate consumption for fabs that abated fluorinated gases used in etch processes and reported through the GHGRP (i.e., **abated fabs**), the first step was to estimate what emissions from these fabs would have been in the absence of abatement (“hypothetical uncontrolled emissions”). This step was completed using the following approach:

1. Calculate total hypothetical fab-wide uncontrolled carbon dioxide equivalent (CO_2 eq) emissions from the abated fab by dividing the total reported GWP-weighted sum of fluorinated GHG and nitrous oxide emissions by (1 minus fab-wide DRE).
2. Sum CO_2 eq emissions of all fluorinated GHGs and nitrous oxide that come from abated processes at that fab.
3. Sum CO_2 eq emissions of all fluorinated GHGs and nitrous oxide that come from unabated processes at that fab.
4. For each HFC, break out emissions from abated vs. unabated processes.

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[5] For each wafer size, a system of simultaneous linear equations, including input gas emission factors and by-product emission factors as coefficients, was used to back-calculate the consumption of each fluorinated GHG from the emissions of each fluorinated GHG.

5. Calculate the hypothetical uncontrolled emissions from abated processes at the fab by subtracting the emissions of unabated processes from the total hypothetical fab-wide uncontrolled CO_2 eq emissions.
6. Where there is exactly one input gas for a chamber cleaning process subtype in a fab and that input gas is abated but the by-product CF_4 is not, calculate the uncontrolled emissions from abated chamber cleaning processes, and then from other abated processes, as follows:
    a) Calculate the hypothetical uncontrolled input gas emissions from the chamber cleaning process subtype by dividing the reported unabated CF_4 emissions by the CF_4 by-product emission factor (EF) for that process subtype and wafer size (yielding the input gas consumed) and then multiplying the result by the input gas EF for that process subtype and wafer size (yielding the uncontrolled input gas emissions).
    b) Calculate the hypothetical uncontrolled emissions from the remaining abated processes in the fab by subtracting the hypothetical uncontrolled NF_3 (or other input gas) emissions calculated in step 6a from the hypothetical uncontrolled emissions from all abated processes calculated in Step 5.
    c) Calculate the actual abated emissions from the remaining abated processes in the fab by subtracting the actual, abated NF_3 (or other input gas) emissions from the abated chamber cleaning processes described in 6 from the actual, abated emissions from all abated processes calculated in Step 2.
    d) For 300-mm fabs where the hypothetical uncontrolled emissions calculated in 6b include emissions only from etching processes (i.e., where all abated chamber cleaning processes meet the criteria in Step 6), calculate the share of emissions from etching processes that is fed into abatement devices by taking into account the controlled emissions of each gas from etching processes, the hypothetical uncontrolled emissions calculated in 6b, and the DREs for etching processes. Then calculate a scale-up factor of $1/(1 - \text{abated share} \times \text{HFC etching DRE})$. Multiply the abated emissions of each HFC by this scale-up factor to calculate hypothetical uncontrolled emissions of each HFC from abated processes.
    e) For 200-mm fabs, divide the hypothetical uncontrolled emissions in 6b by the actual emissions in 6c. Multiply the abated emissions of each HFC by this scale-up factor to calculate hypothetical uncontrolled emissions of each HFC from abated processes.
7. Where the fab does not meet the criteria in step 6, divide the hypothetical uncontrolled emissions from abated processes in step 5 by the actual emissions from abated processes in step 2. Multiply the abated emissions of each HFC by this scale-up factor to calculate hypothetical uncontrolled emissions of each HFC from abated processes.

After the hypothetical uncontrolled emissions of each HFC were calculated, the consumption factors developed based on the analysis of the unabated fabs were applied to estimate consumption for the **abated fabs.** These consumption factors are shown in Table 3.

Table 3. Consumption Factors by Wafer Size, HFC, and Year

	200 mm Wafer Size			300 mm Wafer Size		
	2017	2018	2019	2017	2018	2019
HFC-23	1.28	1.29	1.28	1.84	1.91	2.05
HFC-32	7.69	7.69	7.69	4.24	4.08	4.31
HFC-41	1.43	1.43	1.43	1.46	1.38	1.02

HFC use by **non-reporters** was estimated using the emission estimates prepared for this group for the U.S. Greenhouse Gas Inventory. As described in the Inventory, those estimates are based on the estimated production in total manufactured layer-area (TMLA) of non-reporting fabs along with emission factors (emissions per TMLA) developed for each wafer size based on GHGRP-reported emissions from unabated fabs. These estimated uncontrolled emissions were multiplied by the consumption factors per wafer size used to calculate HFC consumption by abated fabs (based on the **unabated fab** data).

In all calculations, differences for wafer sizes (i.e., 200 mm or 300 mm) were accounted for.

4.3. Estimated Historical Use of HFCs in Semiconductor Manufacturing

Table 4 and Figures 1 and 2 show the estimated HFC use in the semiconductor industry from 2015 to 2019.

Table 4. Estimated Historical HFC Use in the Semiconductor Industry

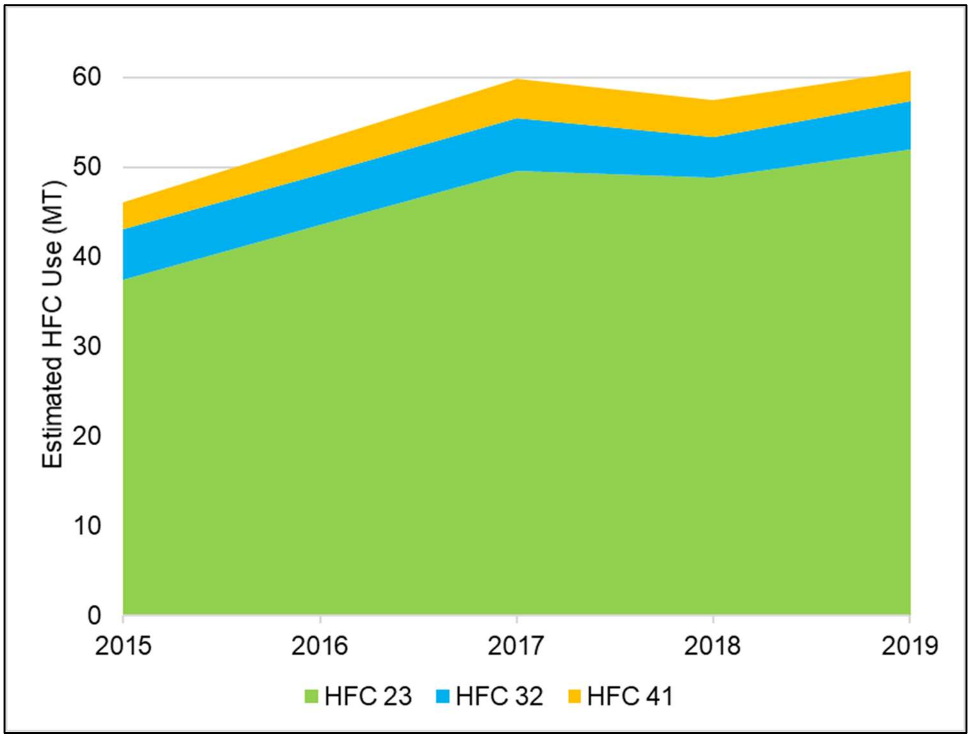
	2015	2016	2017	2018	2019
Historical Use (MT)					
HFC-23	37	44	50	49	52
HFC-32	5.6	5.7	5.9	4.4	5.4
HFC-41	3.1	3.7	4.4	4.1	3.4
Total HFC	46	53	60	57	60
Historical Use (MMT CO_2 eq)					
HFC-23	0.55	0.64	0.73	0.72	0.77
HFC-32	3.8×10^{-3}	3.9×10^{-3}	4.0×10^{-3}	3.0×10^{-3}	3.6×10^{-3}
HFC-41	2.8×10^{-4}	3.4×10^{-4}	4.1×10^{-4}	3.8×10^{-4}	3.1×10^{-4}
Total HFC	0.56	0.65	0.74	0.73	0.77

Totals may not sum due to independent rounding.
Source: GHGRP (2021), WFF (2020)

EPA estimated that there was an increase in HFC use in semiconductor manufacturing from 2015 to 2017, consistent with the steady increase in wafer manufacturing capacity within U.S. fabs (SIA 2020a). There was a slight decline in estimated HFC use in 2018 when compared to 2017 levels, however the overall trend is still increasing.

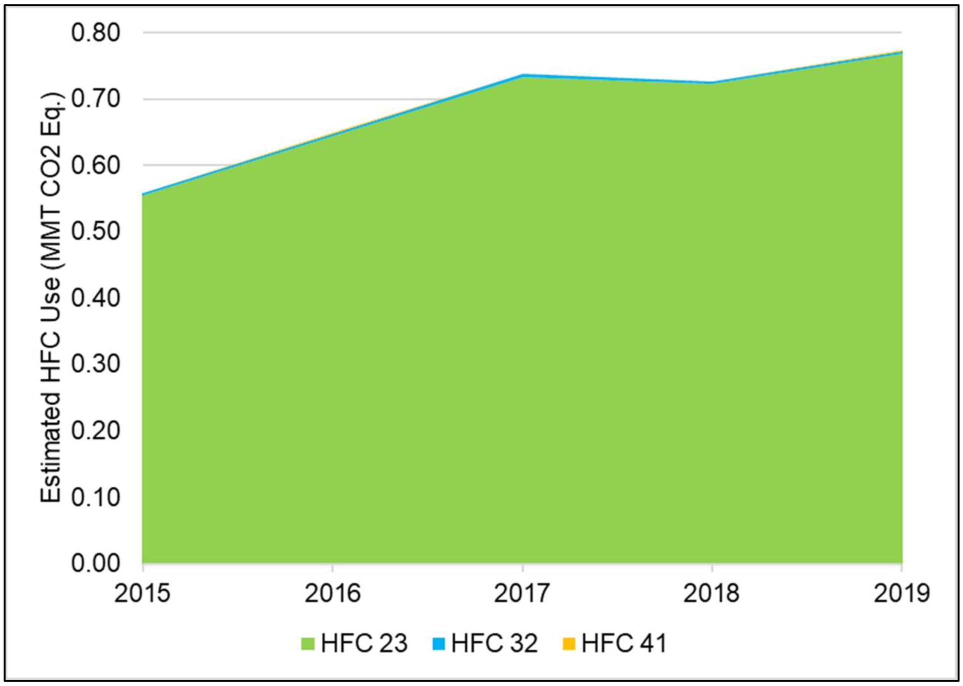
Both the use estimates shown in Table 4 and the projections shown in Section 4.3 are expected to be a slightly lower than the actual use and projected use for the sector due to the method used to estimate consumption at abated fabs. The uncertainties in the analysis are discussed in Appendix A.

Figure 1. Historic Estimated HFC Use in Semiconductor Manufacturing the United States from 2015-2019 (MT)



Source: GHGRP (2021), WFF (2020)

Figure 2. Historic Estimated HFC Use in Semiconductor Manufacturing the United States from 2015-2019 (MMT CO_2 Eq.)



Source: GHGRP (2021), WFF (2020)

4.4. Projected Use of HFCs in Semiconductor Manufacturing

As discussed above, HFC use in semiconductor manufacturing is projected to continue. The use of HFCs and other fluorinated GHGs in semiconductor manufacturing has two main drivers: the production of semiconductors and the complexity of semiconductor devices. Production is expected to increase because semiconductors play a fundamental role in enabling technological innovation throughout the economy. Many growth areas for the U.S. economy, including electric vehicles, Internet of Things, clean energy, and others, are enabled by semiconductor technology (SIA 2021). The anticipated passage of the CHIPS Act would result in a 50-billion-dollar investment in semiconductor manufacturing, and the new construction of seven to ten semiconductor fabs in the United States (White House 2021). Some companies are anticipating tripling in size over the next 24 to 36 months (Electronic Fluorocarbons 2021). The complexity of semiconductor devices, which increases the number of HFC-using steps required to manufacture them, is also expected to increase as device speed and sophistication increase.

Future HFC use in the United States was projected by using the average annual growth in HFC usage in semiconductor production over the past 10 years (i.e., 2011–2019) of 10.1 percent (SIA 2021). The actual growth rate may be higher as the historical average in semiconductor HFC usage does not take into account drivers such as the CHIPS Act.

The introduction of 450mm wafers has been under consideration by the industry for many years, which could change the industry's current patterns of fluorinated GHG use. However, due to its significantly higher costs and need for specialized equipment, it is not anticipated that wide-spread manufacturing of 450mm will occur in the near future (Hruska 2017).

HFC use in 2020 was estimated by multiplying the average use of each HFC between 2017 and 2019 by the historical average annual growth in semiconductor HFC use. Table 5 shows the projected use of HFCs in the semiconductor industry from 2020 to 2025.

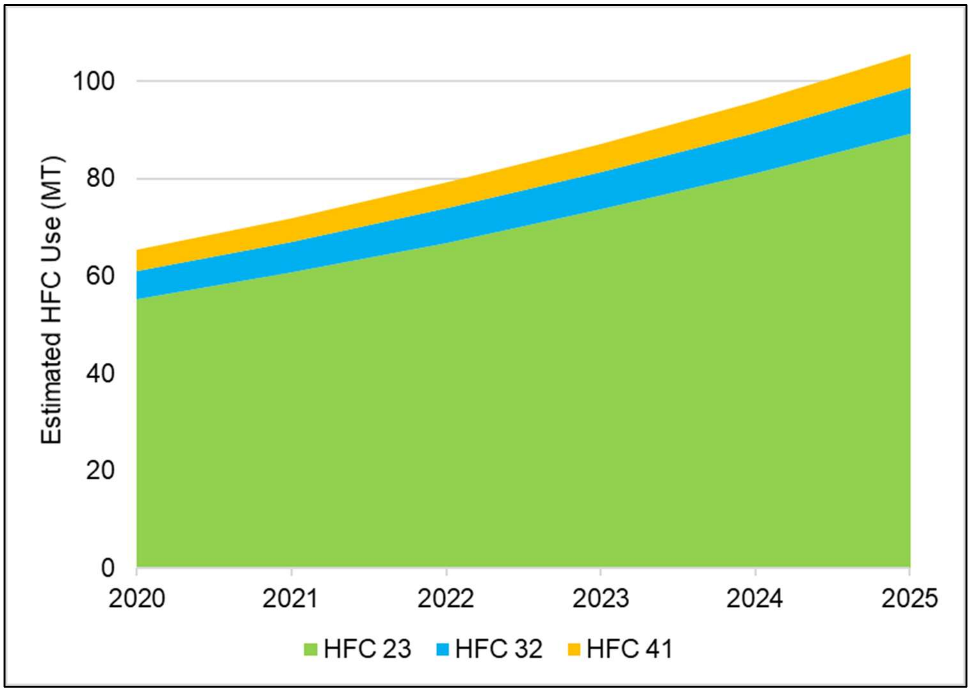
Table 5. Projected HFC Use in the Semiconductor Industry

	2020	2021	2022	2023	2024	2025
Projected Use (MT)						
HFC-23	55	61	67	74	81	89
HFC-32	5.7	6.3	7.0	7.7	8.4	9.3
HFC-41	4.4	4.8	5.3	5.8	6.4	7.1
Total	65	72	79	87	96	106
Projected Use (MMT CO_2 eq)						
HFC-23	0.82	0.90	0.99	1.09	1.20	1.32
HFC-32	3.9×10^{-3}	4.3×10^{-3}	4.7×10^{-3}	5.2×10^{-3}	5.7×10^{-3}	6.3×10^{-3}
HFC-41	4.0×10^{-4}	4.4×10^{-4}	4.9×10^{-4}	5.4×10^{-4}	5.9×10^{-4}	6.5×10^{-4}
Total	0.82	0.90	1.00	1.10	1.21	1.33
Projected Growth (%)	10.1	10.1	10.1	10.1	10.1	10.1

Totals may not sum due to independent rounding.
Source: GHGRP (2021), WFF (2020), SIA (2021)

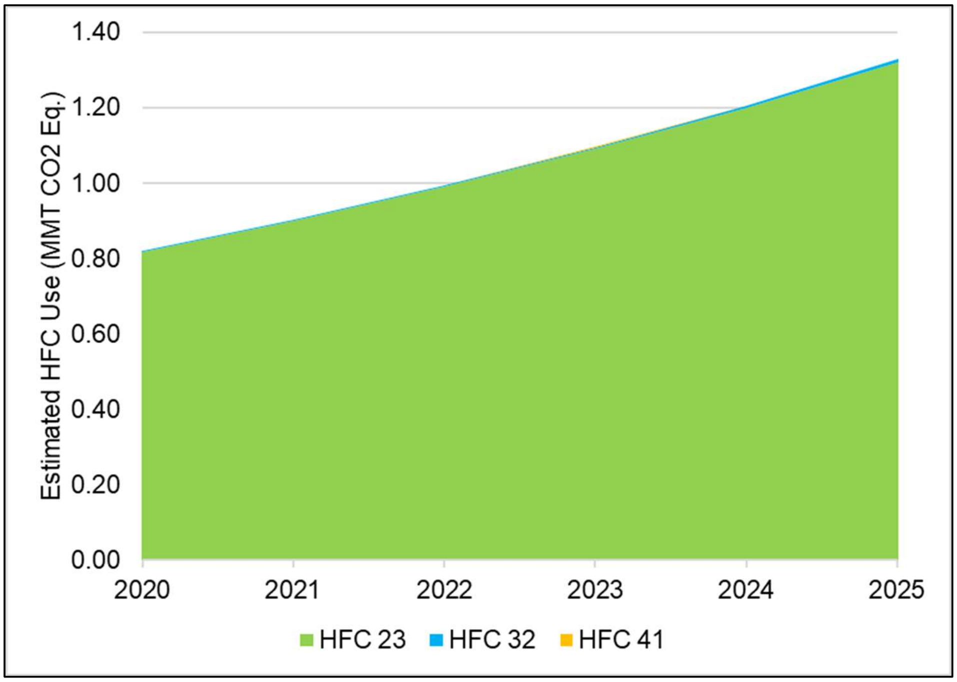
Figure 3 and Figure 4 shows the projected future use of HFCs in U.S. semiconductor manfacturing.

Figure 3. Projected HFC Use in Semiconductor Manufacturing in the United States from 2020-2025 (MT)



Source: GHGRP (2021), WFF (2020), SIA (2021)

Figure 4. Projected HFC Use in Semiconductor Manufacturing in the United States from 2020-2025 (MMT CO_2 eq)



Source: GHGRP (2021), WFF (2020), SIA (2021)

Industry stakeholders indicated that reclaimed HFC gases are not used in semiconductor manufacturing because the purity standards for semiconductor manufacturing are generally stricter than those for other industries. Reclaimed HFC gas is sourced from the largest users of HFC gas, the refrigeration and air conditioning sector, and is often contaminated with other HFCs, HCFCs, or CFCs (e.g., from equipment that has been retrofitted). Reclaimers process these reclaimed gases to industry standards for refrigeration and air conditioning equipment, which has a relatively high tolerance for impurities, often 0.1 percent to one percent.[6] Tolerance levels in the semiconductor industry are significantly lower (i.e., sub-parts per million (ppm)). In addition, some HFC gases utilized in semiconductor manufacturing, such as HFC-41, are not utilized in the refrigeration and air conditioning sector and thus are not available reclaimed. Therefore, use of reclaimed HFCs is not expected to impact projected HFC use (Air Liquide 2021). However, it is not clear whether in the future reclaimed HFCs could be provided to a purifier and then be reprocessed to the same standard.

4.5. Imports and Exports of Semiconductors in the United States

The United States is a leading manufacture of semiconductors and invests heavily in research and development. In 2019, semiconductors were the fifth highest U.S. export (SIA 2020a). The United States is also a leading exporter of HFC gases utilized in the manufacture of semiconductors (SIA 2020a).

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[6] The Air-Conditioning, Heating & Refrigeration Institute (AHRI) Standard 700 specifies the allowable levels of contaminants for each refrigerant.

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Appendix A: Uncertainties in this Analysis

There are three significant sources of uncertainty in this analysis: (1) the extent to which HFC emissions are abated by semiconductor fabs, (2) the correct consumption-to-emissions ratio ("consumption factor") to apply to hypothetical uncontrolled HFC emissions from abated fabs and non-reporting fabs, and (3) the likely growth rate of HFC consumption over the next decade. These uncertainties affect both the magnitudes and trends of HFC emissions.

The extent to which HFC emissions are abated by semiconductor fabs is uncertain because facilities do not report the fraction of each HFC abated to the GHGRP. Instead, they report their overall abatement levels across fluorinated GHGs and process types (fab-wide DREs) and whether or not specific HFCs used in specific process types are abated at all. Because each process type emitting HFCs (or other fluorinated GHGs) is likely to involve multiple manufacturing tools, each of which must be abated separately, some tools emitting a particular HFC (or other fluorinated GHG) may be abated while others are not. In addition, the efficiency with which abatement devices destroy fluorinated GHGs (i.e., the destruction and removal efficiency or DRE) varies by fluorinated GHG. For etching processes, default DREs for fluorinated GHGs other than CF_4 are 96 to 97 percent, but the default DRE for CF_4 is 75 percent. (See 40 CFR Part 98, Subpart I, Table I-16.) In this analysis, hypothetical uncontrolled emissions of abated HFCs are calculated by assuming that the fraction of HFCs fed into abatement devices is the same as the fraction of most other abated fluorinated GHGs fed into abatement devices in each fab.[7] For 300-mm fabs, the difference between the DRE for CF_4 and the DRE for other fluorinated gases from etching processes is also taken into account.[8] For 200-mm fabs that do not abate CF_4 and for 300-mm fabs, this approach is expected to yield an unbiased estimate across the full population of abated fabs unless there are systematic differences between HFCs and other abated fluorinated GHGs in the extent to which their emissions are fed into abatement devices. For example, fabs may abate relatively high fractions of fluorinated GHGs with large GWPs, such as SF_6 (whose GWP is 22,800), while they abate lower fractions of fluorinated GHGs with relatively small GWPs, such as HFC-41 (whose GWP is 92). Since the GWP of the most highly used HFC, HFC-23, is in the middle of the range of GWPs of the fluorinated GHGs used in semiconductor manufacturing, concerns about GWPs may not create large systematic differences in the extent to which HFC-23 is abated compared to other fluorinated GHGs. Nevertheless, such systematic differences cannot be ruled out.

For 200-mm fabs where CF_4 is abated, this method is expected to systematically underestimate hypothetical uncontrolled emissions of abated HFCs due to the differences in the default DREs for CF_4 and the other gases in Table I-16. For fabs where the fab-wide DRE is low or moderate (<60%), the method is expected to underestimate emissions by around 10% or less. Most 200-mm abated fabs fall into this category. However, for fabs where there is significant abatement

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[7] "Most other abated fluorinated GHGs" includes abated fluorinated GHGs other than the fluorinated GHGs emitted from the abated chamber cleaning processes described in Step 6 of the methodology outlined on pages 7 and 8. For the fluorinated GHGs emitted from the abated chamber cleaning processes described in Step 6, the level of abatement can be estimated precisely.

[8] We were not able to take this difference into account for 200-mm fabs because the method for doing so requires separating emissions from etching processes from those from cleaning processes, and we were not able to separate these emissions for most abated 200-mm fabs.

(i.e., fab-wide DREs >70%), the estimated hypothetical uncontrolled emissions of abated HFCs may be significantly lower than the actual hypothetical uncontrolled emissions.

The consumption-to-emissions ratio (“consumption factor”) that is applied to the calculated uncontrolled emissions of abated fabs to estimate their consumption is uncertain for two reasons. First, because emissions of HFCs (especially HFC-23) result both from the use of HFCs as input gases and from the formation of HFCs as by-products from the use of other input gases, the consumption factor that is calculated depends on the relative quantities of the different fluorinated GHGs that are used as input gases in each fab. These quantities vary from fab to fab depending on the types of devices manufactured and the processes used to manufacture them. In this analysis, various methods of calculating consumption factors were evaluated, including weighted averages, straight averages, and regressions of consumption against emissions. For HFC-23, straight averages yielded the lowest consumption factors while regressions yielded the highest, spanning a difference of approximately 20% for both wafer sizes. (The regression analyses showed R^2 values between 92 and 99 percent, depending on the wafer size and year. All regressions were forced through the origin.) The regression coefficient of consumption against emissions was found for each HFC, year, and wafer size, and was used for this analysis. These calculated consumption factors were quite stable across the three years, and when inverted, the resulting implied emission factors were either identical to the subpart I default input gas emission factors for the same HFC and wafer size (e.g., for HFC-32 and HFC-41 used in 200-mm manufacturing) or were somewhat higher than the subpart I default input gas emission factors, as is expected when the HFC is formed as a by-product in addition to being used as an input gas (e.g., for HFC-23 for both wafer sizes). This outcome indicates that the calculated consumption factors are within the expected range.

Second, assuming that the HFC consumption factors calculated for each wafer size are representative of unabated fabs, there may be differences between unabated fabs and abated fabs that make the factors less representative of consumption of abated fabs. Such differences may arise, for example, if abated fabs were built more recently than unabated fabs or if abated fabs make more advanced devices than unabated fabs, both of which could result in use of a different mix of input gases.

Finally, the likely future growth rate of HFC use by semiconductor manufacturers in the U.S. is uncertain because it depends both on the future growth rate of semiconductor manufacturing in the U.S. and on the evolving use of HFCs for this manufacturing. The use of HFCs in turn depends on the number of steps that use fluorinated GHGs in the manufacturing process and on manufacturer’s preferences for HFCs compared to other fluorinated GHGs as input gases for their processes. Both of these parameters have changed over time.