

CHAPTER 6

ELECTRONICS INDUSTRY EMISSIONS

[Parts shaded in grey – the unchanged text from the 2006 IPCC Guidelines]

[Parts in brackets – comments from Authors/issues that may be refined]

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6 ELECTRONICS INDUSTRY EMISSIONS

[This Chapter 6 is an update/elaboration of Chapter 6 Volume 3 of the *2006 IPCC Guidelines* and should be used instead of Chapter 6 Volume 3 of the *2006 IPCC Guidelines*. Substantial changes and new guidance include:

- Guidance on tracking gas consumption and apportioning use to different process types/subtypes;
- An update to the Tier 2a method to account for the fraction of gas used in processes with emission control technologies and emissions control technology uptime;
- An update to the Tier 2b method for semiconductors to account for the size of manufactured wafers and the input gas rather than the process type and input gas;
- A new Tier 2c method for semiconductors that accounts for the size of manufactured wafers in addition to the process type and input gas as well as for the fraction of gas in processes with emission control technologies and emissions control technology uptime;
- A new section on adapting Tier 2 methods to account for technological changes, including guidance on when facility-specific measurements should be considered;
- An update to the Tier 3 method (now labeled Tier 3a) to provide guidance on selecting processes for emissions characterizations (including a discussion of “similarity” among recipes);
- A new Tier 3b method that relies on the measurement of emission factors at the stack level rather than the process level;
- Updated Tier 1 emission factors for heat transfer fluids;
- Updates to the emission factors for Tier 1 and Tier 2 for all electronics industry types (still under development); and
- Corresponding updates to the Completeness; Time Series Consistency; Uncertainty; and QA/QC, Reporting and Documentation sections (still under development).

Note: Because this chapter completely replaces the corresponding chapter in the *2006 IPCC Guidelines*, the equations, tables, figures, and boxes here have all been renumbered in simple sequential order, without reference to the corresponding equations, tables, figures, or boxes in the *2006 IPCC Guidelines* (where those exist).]

6.1 INTRODUCTION

As part of its manufacturing processes, the electronics industry uses greenhouse gases (GHGs) such as fluorinated compounds and nitrous oxide (N₂O) for plasma etching intricate patterns, cleaning substrates and reactor chambers, as well as for temperature control. The specific electronic industry subsectors discussed in this chapter include the manufacturing of semiconductor devices, microelectromechanical systems (MEMS), photovoltaic (PV) devices, and displays, which in turn consist of thin-film-transistors (TFTs) for displays and organic light emitting devices (OLEDs).

The electronics industry currently emits both process greenhouse gas compounds (C) that are gases at room temperature and fluorinated greenhouse compounds (FC) that are liquids at room temperature. The gases include perfluoromethane (CF₄), perfluoroethane (C₂F₆), perfluoropropane (C₃F₈), perfluorocyclobutane (c-C₄F₈), 1,3-hexafluorobutadiene (C₄F₆), octafluorocyclopentene (c-C₅F₈), fluoromethane (CH₃F), difluoromethane (CH₂F₂), trifluoromethane (CHF₃), fluoroethane (C₂H₅F), nitrogen trifluoride (NF₃), sulphur hexafluoride (SF₆), carbonyl fluoride (COF₂), and octafluorotetrahydrofuran (C₄F₈O). These gases are used in two important steps of electronics manufacturing: (i) plasma etching and wafer cleaning of silicon containing materials and (ii) cleaning thin-film tool chamber-walls after processing substrates. Electronic manufacturers also use liquid fluorinated compounds as heat transfer fluids for temperature control during certain processes, as well as during testing of packaged semiconductor devices and during vapour phase reflow soldering of electronic components to circuit boards. In addition, liquid FCs are occasionally used to clean TFT-Display panels during manufacture. These liquid FCs have appreciable vapour pressures and include perfluoropolyethers, perfluoroalkanes, perfluoroethers, tertiary perfluoroamines, perfluoroalkylmorpholines, and perfluorocyclic ethers. More than 40 different liquid FCs are marketed to the electronics industry, often as mixtures of fully fluorinated compounds.

Both plasma etching and thin film deposition (TFD) chamber cleaning use high energies to break the Cs into fluorine atoms to perform these process steps. The majority of C and N₂O emissions result from the failure to completely break down the Cs (or N₂O) that are fed into the process (i.e., the limited utilisation efficiency of the input gases). In addition, a fraction of the input gases used in the production process can be converted into C by-

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products such as CF₄, C₂F₆, C₄F₆, C₄F₈, C₃F₈, CHF₃, CH₂F₂, and CH₃F. Also, formation of CF₄, C₂F₆, CHF₃, CH₂F₂, CH₃F (and potentially other Cs) as by-products of etching or cleaning carbon-containing thin films must be taken into account, in particular for processes using molecular fluorine (F₂), nitrogen trifluoride (NF₃), sulphur hexafluoride (SF₆), or chlorine trifluoride (ClF₃) input gases.¹ It should be noted that CF₄ may be formed in combustion abatement systems using hydrocarbon fuels under certain circumstances with F₂ and remote NF₃ chamber cleans and an appropriate by-product emission factor should be used. The byproduct is assumed to be zero if the abatement OEM or electronics manufacturer can certify that the rate of conversion is <0.1%. This is discussed in detail in the Emission Control Technology for Tier 2 methods section.

With respect to liquid FCs, emissions occur through evaporative losses.

The *2019 Refinement* was designed to maintain the scientific validity of GHG emissions estimates from the electronics industry. Compared to the *2006 IPCC Guidelines*, the *2019 Refinement* takes into account the changes in manufacturing processes and equipment that have occurred in the electronics industry during the thirteen-year interim period, and reflect the much larger set of experimental data available (as of 2019 compared to 2006) to calculate default emissions factors for the sector. Also, several methodological refinements are introduced to provide greater accuracy and flexibility, depending on how reporting companies track gas usage and implement control technologies. The *2019 Refinement* includes six revised methods (Tier 1, 2a, 2b, 2c, 3a, and 3b), compared to three for the *2006 IPCC Guidelines*.

The Tier 1 method uses the same approach as in 2006, where emissions are estimated based on the surface area of substrate produced for each subsector (semiconductor, display, MEMS, PV), but the Tier 1 emissions factors (EFs) have been updated to account for technological advancements and for the use of a broader basket of greenhouse gases. As was the case in the *2006 IPCC Guidelines*, the Tier 1 method does not allow accounting for use of emissions control technologies.

For the semiconductor subsector, the 2006 Tier 2a method is updated with revised emission factors and also accounts for additional precursors and by-products. The 2006 Tier 2b method, which used to distinguish emission factors by process types (etch versus TFD, i.e. Thin Film Deposition) is now replaced with a new Tier 2b method using emission factors applicable to different wafer sizes (≤200mm or ≥300mm in the semiconductor sub-sector), but the revised Tier 2b method no longer distinguishes EFs by process types. Instead, a new Tier 2c method has been added to distinguish EFs by both wafer size (≤200mm or ≥300mm in the semiconductor sub-sector, <6 Generation vs. ≥6 Generation in display sub-sector) and by refined process types (etch or substrate cleaning, remote plasma cleaning, in-situ plasma cleaning, thermal cleaning, TFD, and ‘Other’ (N₂O-using processes that are not TFD)). Finally, compared to the 2006 Guidelines, additional guidance is provided to apportion gas consumption to different process types.

The 2006 Tier 3 method, which was based on process-specific parameters has evolved into the current Tier 3a method, which provides increased guidance for estimating emissions using measured site-specific emissions factors (as opposed to the default emission factors used for the Tier 2 methods). In principle, the Tier 3a method is applicable to all subsectors (semiconductor, display, MEMS, PV. Finally, the 2019 Refinement includes a new ‘stack’ Tier 3b method based on the measurement of site-specific emission factors at the stack level).

6.2 METHODOLOGICAL ISSUES

6.2.1 Choice of Method

6.2.1.1 ETCHING AND TFD CLEANING FOR SEMICONDUCTORS, LIQUID CRYSTAL DISPLAYS, AND PHOTOVOLTAICS

GHG emissions from the electronics industry vary according to the gases and process types and subtypes used in manufacturing, as well as the brand, and the implementation of emission reduction technology. The choice of methods will depend on data availability and is outlined in the decision tree of Figure 6.1 (Decision tree for

¹ When using cleaning or etching gases that do not contain carbon (e.g. F₂, NF₃, SF₆, or ClF₃), CF₄ and other Cs with high GWPs can be formed during the etching or cleaning of carbon-containing thin films, thus resulting in global warming emissions from the process. In particular, it should be noted that emissions of CF₄ and other C by-products with high GWPs should be taken into account, even when the cleaning or etching precursor itself has no global warming potential (such as F₂ or ClF₃). Please see section 6.2.2.1 for more detail.

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estimation of GHG emissions from electronics manufacturing) and in Table 6.1 (Information for sources necessary for completing the tiered emissions estimating methods for electronics manufacturing).

Continuous (in-situ) emissions monitoring is not currently considered an economically viable means to estimate emissions from the electronics industry. Greenhouse gas emissions are periodically measured, however, during the development of new processes and tools, generally for centreline process conditions.² In addition, some facilities may periodically (for short periods of time) install equipment to measure emissions from their stacks for purposes of developing facility-specific emission factors to estimate emissions over the long term. While the Tier 1 and Tier 2a, 2b, and 2c methods are based on averaged (default) emission factors based on a large set of measured processes from a host of sources across industry, the higher tiered methods are based on measured emission factors (Tier 3a), or site-specific emission factors derived from stack measurements (Tier 3b).

It is very important to note that emission factors (i.e. input gas utilisation efficiencies and by-product formation rates) can be strongly affected by changes in process variables (e.g. substrate size, process type/subtype, film removed in TFD chamber cleans, tool platform, combination of gases used, etc.), and that emission factors for a recipe ‘tuned’ for a particular purpose or product can differ from those of the centreline process recipe that may have been used for measuring emissions. Further, emission factors are affected by the design of the process reactors and will substantially fluctuate from one tool manufacturer to another, even when the process function is similar (e.g. deposition of un-doped silicon dioxide using N₂O, cleaning a TFD reactor after deposition of silicon nitride using NF₃, etching of a trench in an interconnect structure using C₄F₆, etc.). In addition, the efficacy of greenhouse gas emission control equipment depends on whether it is designed to abate the target gas and on operating and maintaining the equipment according to the manufacturer’s specifications. As presented in Figure 6.1 and Table 6.1, the choice of a particular method will depend on the availability of information regarding substrate production capacity, the consumption of input gases, the utilisation and conversion of input gases within process tools, as well as on the abatement efficiency of all input gases and by-products. The accuracy of estimated emissions depends on the method used. Generally, the higher tiered methods will be more accurate than the lower tiers, and using site-specific emission factors will improve accuracy and greatly reduce the uncertainty of emissions estimates. The accuracy of the methods using default emission factors (Tier 1, Tier 2a, 2b, 2c) essentially depends, inter alia, on the differences between the emission factors of the processes actually used in production and the averaged (default) emission factors of a particular method, as well as on potential errors in apportioning gas consumption, and in reporting abatement efficiency and uptime. With respect to uncertainty, the confidence level of a particular estimate is principally driven by the uncertainty of the default emission factors, which frequently show relative errors of greater than 100% (see Table 6.9) and of gas consumption tracking and apportioning. Thus, the use of higher tiered methods is strongly encouraged, especially in the case where default emission factors do not exist. Where no gas consumption data is available, emissions can be estimated using the Tier 1 method based on production figures (surface area of substrate used during the production of electronic devices), but this approach is the least accurate and should be used only in cases where company-specific gas consumption data is not available. Further, the Tier 1 method does not allow to account for the use of emission control technology. The choice of method will also depend on whether companies track gas usage by substrate size and/or by process type, which are the key criteria for selecting between the Tier 2a, 2b, and 2c methods.

The key distinction between the Tier 2a and Tier 2b methods is that the Tier 2b method provides emissions factors that depend on wafer size ($\leq 200\text{mm}$ or $\geq 300\text{mm}$ for the semiconductor sub-sector). The Tier 2a method does not distinguish between substrate size and should only be used in the case of facilities processing multiple substrate sizes where it is not possible to distinguish (apportion) gas consumption between the different substrate sizes. It should also be noted that the Tier 2a and 2b methods do not allow for distinguishing emission factors by process type; however, a limited amount of apportionment NF₃ and C₃F₈ emission factors are different for the remote clean technology and for ‘other’ (NF₃- or C₃F₈-using) processes, and that the N₂O emission factors are different for N₂O TFD processes and for ‘other’ N₂O-using processes (for all other gases there are no distinctions in the Tier 2a and Tier 2b methods between TFD chamber cleaning, etch, or substrate cleaning processes). Because emission factors are generally dependent on process type, the Tier 2a and 2b methods should only be used when it is not possible to distinguish (apportion) gas consumption between TFD chamber cleaning technologies, etch, or substrate cleaning processes, or in cases where the gas consumption apportionment model proves to introduce greater uncertainty than using the more accurate process-type-dependent Tier 2c emission factors.

The Tier 2c method is the preferred Tier 2 sub-method and is believed to provide more accurate emission estimates than other Tier 1 or Tier 2 methods because the Tier 2c default emission factors distinguish between both substrate

² Centreline conditions refer to specific process conditions of gas flows, chamber pressure, processing time, plasma power, etc., for which an electronic device manufacturer may have measured emissions, or specific process conditions that may have been provided by a tool manufacturer who standardized its equipment for sale. Note that it is common for electronic devices Manufacturers to modify centreline process conditions (developed in-house or by tool manufacturers) to optimise for particular needs or for a particular product.

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size and process type. In the case of the Tier 2c method, the process-types are defined as 1) etching and wafer cleaning, 2) remote plasma cleaning, 3) in-situ plasma cleaning, 4) in-situ thermal cleaning, 5) N₂O TFD, and 6) N₂O ‘other’. It should be noted that distinguishing emission factors by process type require apportionment of gas consumption to each process type; for example, if NF₃ is used for both remote plasma cleaning, in-situ plasma cleaning, and etching, then the amount of NF₃ consumed for each of these three process types must be apportioned.

BOX 6.1(NEW)
FLUORINATED GREENHOUSE GAS BY-PRODUCTS

(This box is provided for information purposes only)

As discussed briefly in the introduction, the formation of CF₄, C₂F₆, CHF₃, CH₂F₂, CH₃F (and potentially other fluorinated greenhouse gases) as by-products of etching or cleaning carbon-containing thin films must be taken into account. To this effect, by-product emission factors (BCF_{4,i}, BC₂F_{6,i}, BCHF_{3,i}, BCH₂F_{2,i}, and BCH₃F_i emission factors indicating the mass ratio of by-product ‘j’ produced from the use of input gas ‘i’) are included as part of the default emission factors tables for the Tier 2 methods, even when the etching or cleaning gas ‘i’ itself contains fluorine but does not contain carbon. This is because the fluorine atoms and other excited F species generated from the decomposition of NF₃, SF₆ or F₂ can react with the carbon contained in the film to form CF₄ and other carbon-containing greenhouse gas by-products. Such reactions are particularly significant during the etching or cleaning of ‘low k’ (low dielectric constant) materials that often present high carbon content, but formation of carbon-containing by-products also occur when small amounts of carbon are present in the film, for example in the case of thin films deposited with organic precursors such as tetraethylorthosilicate (TEOS). However, when using NF₃, SF₆, F₂ or other etching or cleaning precursors that do not contain carbon, AND when the film being etched or cleaned does not contain carbon, then no CF₄ or other carbon-containing greenhouse gases are formed during the process. Thus, in such cases (and in such cases only), the BPE factors may be equated to zero. It should be noted, however, that sometimes both carbon-containing and non-carbon-containing films are included in the film stacks forming final electronic devices. In such cases, there are two options: 1) if it is practical to track the gas consumption used to clean or etch films containing carbon vs. not containing carbon, the non-zero and zero BPE factors may be applied accordingly, or 2) if it is not practical or desired to track gas consumption to this level of detail, the non-zero BPE factors should be applied to all consumption of a gas if ANY film containing carbon is run with that gas during the year.

The methods believed to provide the most accurate and least uncertain estimates of greenhouse gas emissions for electronic devices manufacturing are the Tier 3a and Tier 3b methods. The Tier 3a method uses the same equations as the Tier 2c method, but –instead of using default emission factors and being limited to five process types– uses, at least in part, measured facility-specific emission factors. In theory, the Tier 3a method could be used to assign an emission factor to each centreline process, or to assign a specific destruction removal efficiency to a particular gas or by-product and abatement system. It should be noted however, that the new Tier 3a method provides more flexibility than the 2006 Tier 3 method, and that using the refined Tier 3a method does not require using a complete set of measured values. While the Tier 3a method is based on a ‘bottom-up’ approach, where reporting companies measure and add up emissions from individual process runs, the Tier 3b method is based on a ‘top-down’ approach, where reporting companies measure emission factors at the stack (end of pipe) level. In the case of the Tier 3b method, reporting companies estimate their emissions based on fab-specific stack emission factors. These emission factors are developed through periodic measurements of stack emissions correlated to 1) the consumption of input gases by the production tools connected to the stack, and 2) the efficacy of the emissions control technologies used with those tools.

With respect to accounting for emissions control technologies, it should be noted that the 2019 Refinement includes a significant elaboration, which is the consideration of the uptime of abatement systems. Also, guidance is provided to determine the suitability of using particular abatement technologies (e.g., cartridge, catalyst, hot-wet, plasma, combustion, new technology) for specific gases. Further, an applicability condition for using default DRE values (Tier 2 and Tier 3 methods) is to obtain a certification by the abatement system manufacturers that their abatement systems are capable of removing a particular gas to at least the default DRE in the worst-case flow conditions, as defined by each reporting site. Guidance is also provided for using site-specific (measured) destruction removal efficiencies to claim higher DREs than the default values.

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Finally, it should be noted that, even though the logic depicted in Figure 6.1 does not show the possibility of combining tiers, such an approach can be used to improve the accuracy of emissions estimates. If default emission factors are not available under Tier 2 (e.g., a new process type/subtype is introduced), facilities can undertake process emissions characterization under Tier 3a and measure (1-U) and BPE factors for those new processes without defaults while using Tier 2 defaults for existing processes. Similarly, the Tier 2c method might be used for a particular sub-section of a facility and then combined with the Tier 3b method to estimate emissions from another sub-section of a facility, where emissions estimates would be based on measured (stack) emission factors. However, reporting companies should not combine the Tier 1 method with any other method.

TABLE 6.1 (UPDATED)							
INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR ELECTRONICS MANUFACTURING							
Data		Tier 1	Tier 2			Tier 3	
			2a	2b	2c	3a	3b
Process Gas Entering Tools	C_i = consumption of gas i		Me/Mo	Me/Mo			
	$C_{i,p}$ = consumption of gas i for process p . ^a				Me/Mo ^a	Me/Mo ^a	
	$C_{i,j}$ = kg of gas i fed into tools connected to stack j .						Me/Mo
	FC = kg of liquid fluorinated compounds						
	h_i = Fraction of gas remaining in shipping container after use (heel) for gas i .		D/Me	D/Me	D/Me	D/Me	D/Me
Process Gas Reactions and Conversion in Tools	U_i = Use rate (fraction destroyed or transformed) for each gas i .		D	D			
	$U_{i,p}$ = Use rate (fraction destroyed or transformed) for each gas i and process p .				D ^a	Me ^a	
	$U_{i,j}$ = Process utilization rate for input gas i for stack system j .						Me
	$B_{k,i}$ = Emission factor for by-product k for input gas i .		D	D			
	$B_{k,i,p}$ = Emission factor for by-product k for input gas i and process p .				D ^a	Me ^a	
	$B_{j,k}$ = By-product formation rate of gas k created as a by-product per amount of input gas i (kg) consumed by tools connected to stack system j						Me

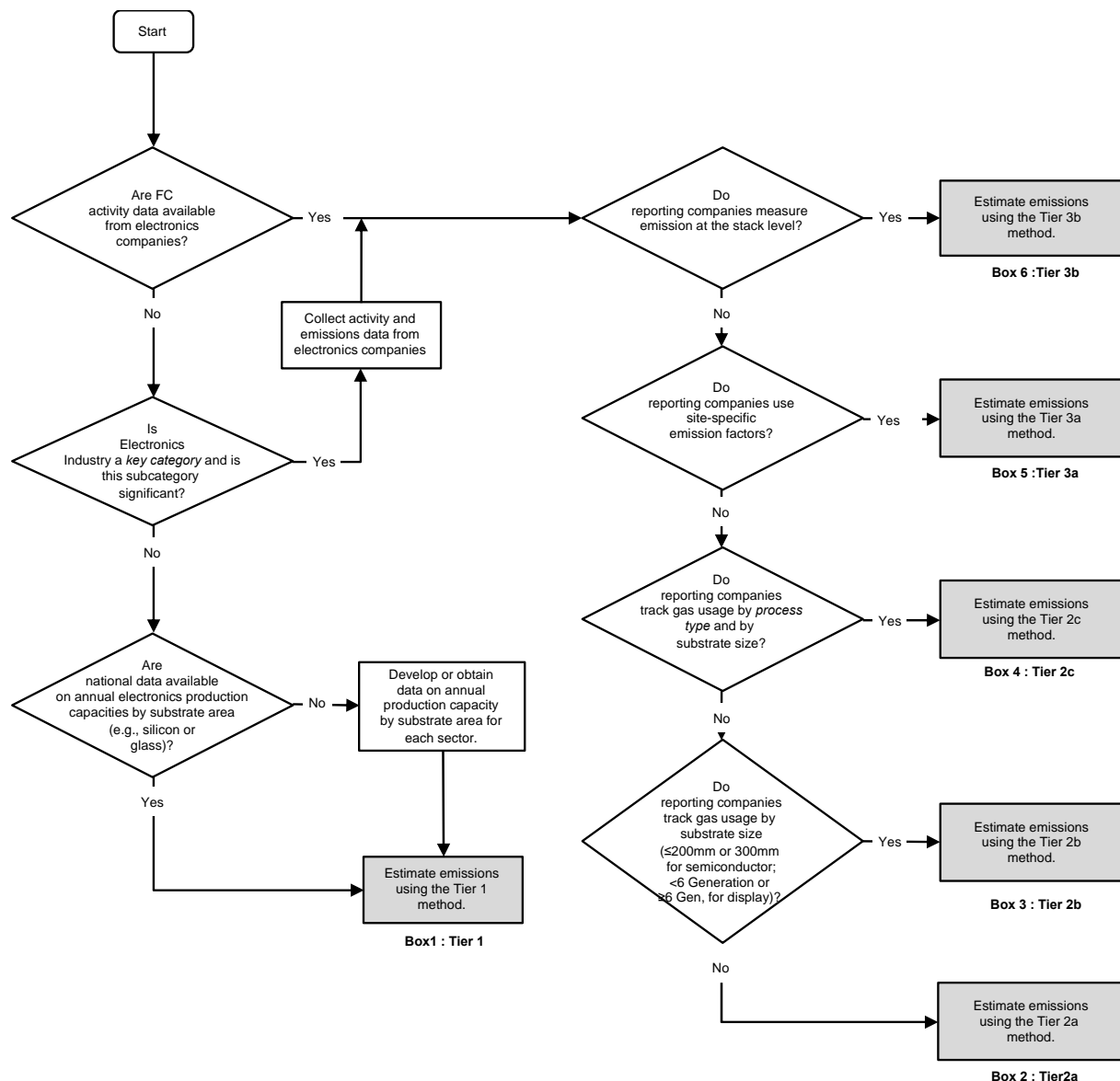
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Downstream Process Greenhouse Gas Emission Control	a_i = Fraction of gas i volume used in processes with certified greenhouse gas emission control technology		Me/Mo	Me/Mo			
	$a_{i,p}$ = Fraction of gas i volume fed into processes p with certified greenhouse gas emission control technology				Me ^a /Mo	Me ^a /Mo	
	a_{ij} = Ratio of the number of tools using input gas i that have abatement systems that are vented to stack system j						Me
	d_i = Destruction Removal Efficiency (DRE) for gas i		D/Me	D/Me			
	$d_{i,p}$ = Destruction Removal Efficiency (DRE) for gas i for process p				D/Me ^a	D/Me ^a	
	D_{ij} = Fraction of input gas i destroyed or removed in abatement systems connected to process tools that are vented to stack system j						Me
	D_{jk} = Fraction of by-product gas k destroyed or removed in abatement systems connected to stack j						Me
	UT = average uptime factor of all abatement systems connected to process tools		Me	Me			
	UT _p = average uptime factor of all abatement systems connected to process tools running process type p				Me ^a	Me ^a	
	UT _j = The average uptime factor of all abatement systems connected to process tools vented to stack j						Me
	UT _{ijk} = The average uptime factor of all abatement systems connected to process tools in the fab emitting by-product gas k , formed from input gas i connected to tools vented to stack j						Me
	n_a = number of etch and wafer cleaning tools equipped with suitable abatement technology		Me	Me			
	m_a = number of TFD tools equipped with suitable abatement technology		Me	Me			
	n = total number of etch and wafer cleaning tools		Me	Me			
	m = total number of TFD tools		Me	Me			
	Td _n = total time, in minutes, that abatement system n connected to process tool(s) is not in operational mode when at least one of the manufacturing tools connected to abatement system n is in operation		Me				
	UT _n = total time, in minutes per year, in which abatement system n has a least one associated manufacturing tool in operation.		Me/D				
	TD _{n,p} = total time, in minutes, that abatement system n connected to process tools running process type p is not in operational mode when at least one of the manufacturing tools connected to the abatement system n is in operation.			Me			
	UT _{n,p} = total time, in minutes per year, in which abatement system n has a least one associated manufacturing tool running process type p in operation.			Me			
Annual Production Capacity	AB _{i,CF4} = CF ₄ emissions from POU abatement generated from the combination of F ₂ or Remote NF ₃ and combustion fuel gas.		D/Me	D/Me	D/Me	D/Me	
	P = Annual production in surface area of substrate produced	Me					
	F _{PV} = fraction of PV manufacture that uses process greenhouse gases (PV subsector only)	Mo					

Me = measurement; Mo = model {modelling criteria TBD}; D = Use default factors from guidance.

^a Depending on the method used, 'p' is to be interpreted as a particular process type (Tier 2c) or a site-specific process (Tier 3a).

Figure 6.1(updated) Decision tree for estimation of GHG emissions from electronics manufacturing



Note:

For a new substrate size, facilities should test and develop measured emission factors (Tier 3a). See section, “ADAPTING TIER 2 METHODS TO ACCOUNT FOR TECHNOLOGICAL CHANGES”. Measured factors can be phased in over time; previous generation Tier 2c default factors can be used during the phase in period. Tier 3a measured factors should be submitted to IPCC EFDB to allow development of Tier 2 defaults.

TIER 1 METHOD – DEFAULT

The Tier 1 method is the least accurate estimation method and should be used only in cases where company-specific gas-consumption data are not available. The Tier 1 method is based on production figures (surface area of substrate used during the production of electronic devices, e.g. silicon, glass). Unlike the Tier 2 or Tier 3 methods, the Tier 1 method is designed to give an aggregated estimate of greenhouse gas and N₂O emissions with an estimated but uncertain break-out among specific gases. Estimates are made simultaneously for all the gases listed in Table 6.2, and the Tier 1 method can only be used if these gases are reported as a complete set. For each class of electronic products being manufactured (semiconductors, display, PV, MEMS), the calculation of emissions relies on a different set of default, gas-specific emission factors. Each default emission factor expresses the average emissions of the relevant gas per unit area of the relevant substrate used during manufacture (including test substrates).

For any class of electronic products (input material), the default emission factors are multiplied by the annual production (P, in units of giga square meters (Gm²)). The result is a set of annual emissions estimates expressed in kg of the gases emitted during the manufacture of that class of electronic products. Because the use of greenhouse gases varies widely during PV manufacture, a third factor to account for the proportion of PV manufacture that employs process greenhouse gases is needed to estimate emissions from PV cells manufacturing. The Tier 1 formula is shown in Equation 6.1.

$$\text{EQUATION 6.1 (UPDATED)}$$

$$\text{TIER1 METHOD FOR ESTIMATION OF THE SET OF C EMISSIONS}$$

$$\{C_i\}_n = \{EF_i \cdot P \cdot [F_{PV} \cdot \delta + (1 - \delta)]\}_n \quad (i = 1, \dots, n)$$

Where:

$\{C_i\}_n$ = emissions of greenhouse gas compound i , mass of gas i .

Note: $\{ \}_n$ denotes the set for each class of products (semiconductors, display, MEMS or PV) and n denotes the number of gases included in each set ($\{ \}$ for semiconductors, $\{ \}$ for display, $\{ \}$ for MEMS, and $\{ \}$ for PV, see Table 6.2.). The estimates are only valid if made and reported for all members of the set using this Tier 1 methodology.

EF_i = C emission factor for gas i expressed as annual mass of emissions per square meters of substrate surface area for the product class, (mass of gas i)/m².

P = annual production, Gm² of substrate used (surface area of substrate used during the production of electronic devices, including test substrates). If annual production is not available from an electronics producer, P may be calculated as the product of the annual manufacturing capacity and annual plant production capacity utilisation (fraction) of that producer.

F_{PV} = fraction of PV manufacture that uses FCs, fraction.

δ = 1 when Equation 6.1 is applied to PV industry and zero when Equation 6.1 is applied to either semiconductor or TFT-Display industries, dimensionless.

This method does not account for differences among process types (etching versus cleaning), individual processes, or tools. It also does not account for the possible use of emission-control devices.

In using Tier 1, inventory compilers should not modify, in any way, the set of the gases assumed in Table 6.2. For any given manufacturing facility, inventory compilers should not combine emissions estimated using Tier 1 method with emissions estimated using the Tier 2 or 3 methods. Neither may inventory compilers use, for example, the Tier 1 factor for CF₄ to estimate the emissions of CF₄ from semiconductors and combine it with the results of other FC gases from a Tier 2 or Tier 3 method. (See also Section 6.2.2.1.)

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TIER 2 METHODS**GAS CONSUMPTION AND APPORTIONING**

In using Tier 2 and Tier 3 methods, gas consumption (C_i) must be determined and apportioned ($C_{i,p}$). Total annual input gas i consumption (C_i) on a fab basis for each fluorinated GHG and N₂O is calculated using Equation 6.2 below.

$$\text{EQUATION 6.2 (NEW)} \\ \text{CONSUMPTION OF INPUT GAS I} \\ C_i = (IB_i - IE_i + A_i - T_i)$$

Where:

C_i = Annual consumption of input gas i , on a fab basis (kg per year).

IB_i = Inventory of input gas i stored in containers at the beginning of the reporting year, including heels, on a fab basis (kg). For containers in service at the beginning of a reporting year, account for the quantity in these containers as if they were full.

IE_i = Inventory of input gas i stored in containers at the end of the reporting year, including heels, on a fab basis (kg). For containers in service at the end of a reporting year, account for the quantity in these containers as if they were full.

A_i = Acquisitions of input gas i during the year through purchases or other transactions, including heels in containers returned to the electronics manufacturing facility, on a fab basis (kg).

T_i = Transfers of input gas i through sales or other transactions during the year, including heels in containers returned by the electronics manufacturing facility to the chemical supplier, as calculated using Equation 6.3, on a fab basis (kg).

Transfers (T_i) are calculated using Equation 6.3.

$$\text{EQUATION 6.3 (NEW)} \\ \text{TRANSFERS OF INPUT GAS I}$$

$$T_i = \sum_{l=1}^M (h_{il} \cdot N_{il} \cdot f_{il})$$

Where:

T_i = Transfers of input gas i through sales or other transactions during the reporting year on a fab basis, including heels in containers returned by the electronics manufacturing fab to the gas distributor (kg).

h_{il} = Gas-specific heel factor for input gas i and container size and type l (expressed as a decimal fraction). A default $h_{il}=0.1$ may be used instead of developing gas specific, container specific factors.

N_{il} = Number of containers of size and type l used at the fab and returned to the gas distributor containing the standard heel of input gas i .

F_{il} = Full capacity of containers of size and type l containing input gas i (kg).

i = Input gas.

l = Size and type of gas container.

M = The total number of different sized container types on a fab basis. If only one size and container type is used for an input gas i , $M = 1$.

A fab-specific heel factor for each type of gas and container used in a facility (h_{il}) can be determined by monitoring the pressure and converting the pressure to mass using the ideal gas law, or based on the weight of the gas provided to the facility in gas supplier documents. If the fab uses less than 50 kg of a fluorinated GHG or N₂O in one reporting year, it may assume that any h_{il} for that fluorinated GHG or N₂O is equal to zero.

For Tier 2 and Tier 3 methods, varying degrees of gas use apportioning are required. Tier 2a and 2b require apportioning of NF₃ and C₃F₈ between Remote and Other, while N₂O is apportioned between N₂O TFD and N₂O other. Apportioning is calculated using Equation 6.4.

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EQUATION 6.4 (NEW)
APPORTIONING OF C TO PROCESS TYPES/SUB-TYPES

$$C_{i,p} = C_i \bullet f_{i,p}$$

Where:

$C_{i,p}$ = The annual amount of input gas i consumed, on a fab basis, for process sub-type or process type p (kg).

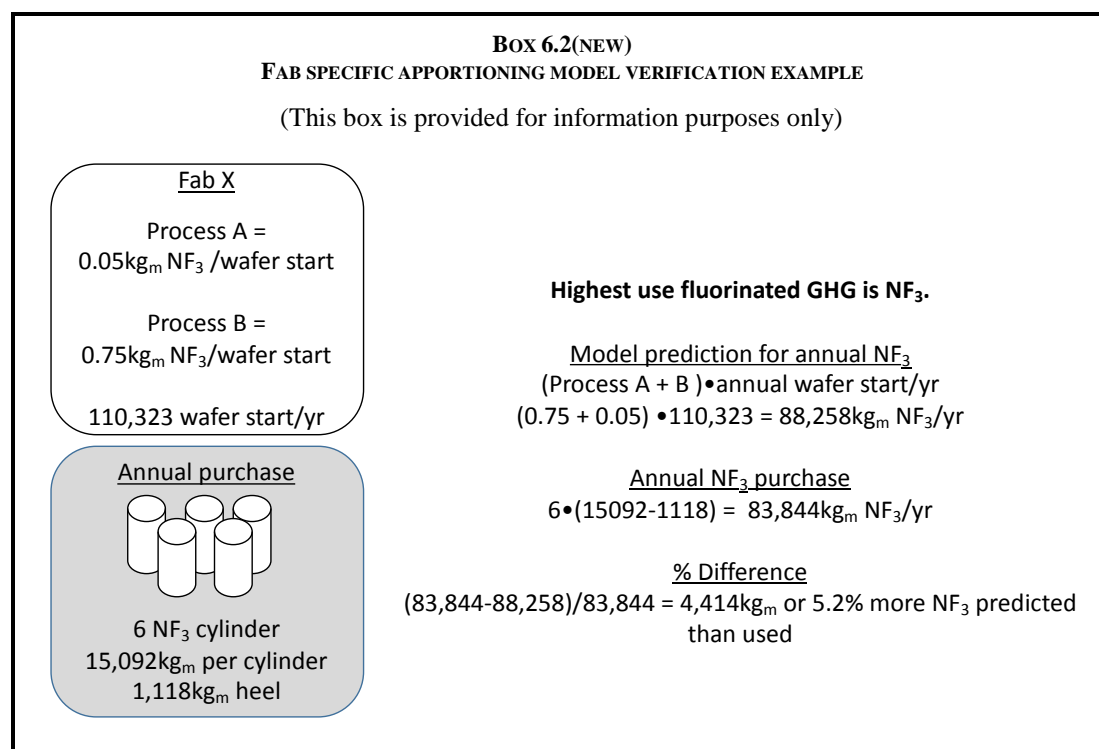
$f_{i,p}$ = Process sub-type-specific or process type-specific j, input gas i apportioning factor (expressed as a decimal fraction).

C_i = Annual consumption of input gas i, on a fab basis, as calculated using Equation 6.2 of this section (kg).

i = Input gas.

Apportioning factors ($f_{i,p}$) should be calculated using a fab-specific engineering model. This model should be based on a quantifiable metric, such as wafer passes or wafer starts, or direct measurement of input gas consumption. To verify your model, you should demonstrate its precision and accuracy by adhering to the following requirements.

- (1) Demonstrate that the fluorinated GHG and N₂O apportioning factors are developed using calculations that are repeatable (repeatable means that the variables used in the formulas for the facility's engineering model for gas apportioning factors are based on observable and measurable quantities that govern gas consumption rather than engineering judgment about those quantities or gas consumption.)
- (2) Demonstrate the accuracy of your fab-specific model by comparing the actual amount of input gas i consumed and the modeled amount of input gas i consumed in the fab, as follows:
 - (i) Analyze actual and modeled gas consumption for a period when the fab is at a representative operating level (Representative operating levels means operating the fab, in terms of substrate starts for the period of testing or monitoring, at no less than 50 percent of installed production capacity or no less than 70 percent of the average production rate for the reporting year, where production rate for the reporting year is represented in average monthly substrate starts. For the purposes of stack testing, the period for determining the representative operating level should be the period ending on the same date on which testing is concluded.) lasting at least 30 days but no more than the reporting year.
 - (ii) Compare the actual gas consumed to the modeled gas consumed for the highest use fluorinated GHG which is used in multiple process types/subtypes reported for the fab (e.g., NF₃ used in remote clean and other processes). You may compare the actual gas consumed to the modeled gas consumed for two fluorinated GHGs and demonstrate conformance on an aggregate use basis for both fluorinated GHGs if one of the fluorinated GHGs selected for comparison corresponds to the largest quantity, on a mass basis, of fluorinated GHGs used at each fab that requires apportionment during the reporting year.
 - (iii) Demonstrate that the comparison performed for the largest quantity of gas(es), on a mass basis, consumed in the fab, does not result in a difference between the actual and modeled gas consumption that exceeds 20 percent relative to actual gas consumption, reported to two significant figures using standard rounding conventions.
 - (iv) If 20% is not achieved, model should be revised until difference between actual and modeled gas consumption does not exceed 20%.
- 3) As an alternative to developing apportioning factors for fluorinated GHG and N₂O consumption using a fab-specific engineering model, you may develop apportioning factors through the use of direct measurement using gas flow meters and weigh scales to measure process sub-type, process type, stack system, or fab-specific input gas consumption. You may use a combination of apportioning factors developed using a fab-specific engineering model and apportioning factors developed through the use of direct measurement.



TIER 2A METHOD

The Tier 2a method is based on default emission factors calculated over all processes and substrate sizes, representing average utilisation efficiencies of the gases used in manufacturing processes (U_i) and the formation of by-products during the used of each input gas 'i' ($B_{CF_4,i}$, $B_{C_2F_6,i}$, $B_{C_3F_8,i}$, $B_{C_4F_6,i}$, $B_{C_4F_8,i}$, $B_{C_5F_8,i}$, $B_{CH_3F,i}$, $B_{CH_2F_2,i}$, or $B_{CHF_3,i}$). Please see Table 6.3 for the Tier 2a default emission factors for semiconductors. These default emission factors represent industry averages over all processes and substrate sizes. Hence, unlike the Tier 2b, Tier 2c and Tier 3 methods that are explained later in this section, the Tier 2a method does not distinguish between substrate sizes ($\leq 200\text{mm}$ vs. $\geq 300\text{mm}$ for semiconductors, < 6 Generation vs. ≥ 6 Generation for display), process types (e.g. etching vs. cleaning), or site-specific processes. However, for all Tier 2 methods, including the Tier 2a and 2b methods, different default emission factors are provided for C_3F_8 remote plasma cleaning vs. 'other' C_3F_8 -using processes, for NF_3 remote plasma cleaning vs. 'other' NF_3 -using processes, and for N_2O TFD processes vs. 'other' N_2O -using processes. Thus, when using the Tier 2a method, the consumption of C_3F_8 , NF_3 , and N_2O and, for display, SF_6 , should be apportioned between their different uses, as applicable to each reporting site.

Concurrently with using the default emission factors as described above, the Tier 2a method calculates emissions for each input gas i used on the basis of site-specific data on gas consumption and on the effective use of emission control technologies. First, the consumption of gas i (C_i) takes into account the heel factor (h_i), which represents the fraction of gas i remaining in the shipping container after use, and which can be based on industry-wide default or site-specific measured values {a sentence addressing developing site-specific h_i values is added in gas consumption and apportioning section}. Second, the overall abatement of process gases and by-products is calculated based on site-specific information, factoring in the fraction of gas used in processes with emission control technologies (a_i), the destruction removal efficiency of the gases (d_i), and the uptime of abatement systems (UT). Thus, to use the Tier 2a method inventory compilers must have direct communication with industry (e.g., annual emissions reporting) to gather consumption data and ensure that emission control technologies are installed and used in accordance with the guidelines provided in this document.

Total emissions are equal to the sum of emissions from all unreacted gases i used in the production process (E_i) plus the emissions of all by-products k (BPE_k) resulting from the conversion of all input gases i used during production, as calculated using Equations 6.5, and 6.6 below.

In the case where a new input gas is used for which no default emission factor ($1-U$) has been established, facilities can estimate emissions using Tier 2 and assume a default emission factor ($1-U$) = 1.0. Alternatively, facilities can undertake process emissions characterization under Tier 3a and measure ($1-U$) and BPE factors for those new processes without defaults while using Tier 2 defaults for existing processes.

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EQUATION 6.5 (UPDATED)**EMISSIONS OF INPUT GAS I**

$$E_i = (1 - h_i) \cdot C_i \cdot (1 - U_i) \cdot (1 - D_i)$$

Where:

 E_i = emissions of unreacted input gas i , kg. h_i = fraction of input gas i remaining in shipping container (heel) after use, fraction. C_i = consumption of input gas i (i = CF₄, C₂F₆, C₃F₈, C₄F₆, c-C₄F₈, C₅F₈, c-C₄F₈O, CHF₃, CH₂F₂, CH₃F, C₂H₅F, COF₂, F₂, N₂O, NF₃, SF₆), kg. U_i = use rate of gas i (fraction destroyed or transformed in process), fraction. D_i = Overall reduction of gas i emissions, fraction, calculated per Equation 6.7.**EQUATION 6.6 (UPDATED)****BY-PRODUCT EMISSIONS**

$$BPE_k = \sum_i (1 - h_i) \cdot [B_{k,i} \cdot C_i \cdot (1 - D_k)] + C_i \cdot AB_{i,CF4}$$

Where:

 BPE_k = emissions of by-product k generated from the conversion of all input gases i , kg. h_i = fraction of input gas i remaining in shipping container (heel) after use, fraction. C_i = consumption of input gas i , kg. $B_{k,i}$ = emission factor, kg gas k created/kg gas i used ($BPE_{k,i}$ = B_{CF₄,i}, B_{C₂F₆,i}, B_{CHF₃,i}, B_{C₃F₈,i}, B_{C₄F₆,i}, B_{C₄F₈,i}, B_{C₅F₈,i}, B_{CH₃F,i}, and B_{CH₂F₂,i}). D_k = overall reduction of gas k by-product emissions, fraction, calculated per Equation 6.7 (replacing i by k indexes). $AB_{i,CF4}$ = Fraction of NF₃ in process exhaust gas that is converted into CF₄ by direct reaction with hydrocarbon fuel and F₂ gas in a combustion abatement system. $AB_{F2,CF4}$ = Fraction of F₂ in process exhaust gas that is converted into CF₄ by direct reaction with hydrocarbon fuel gas in a combustion abatement system. These are set to zero if the abatement OEM or electronics manufacturer can certify that the rate of conversion is <0.1%, otherwise use a default value, e.g. 0.093 kg CF₄ per kg NF₃ and 0.116 kg CF₄ per kg F₂. This will be taken into account in calculations in Tiers 2 & 3.**EQUATION 6.7 (ELABORATION)****EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL TECHNOLOGY**

$$D_i = a_i \cdot d_i \cdot UT$$

Where:

 D_i = overall reduction of gas i emissions, fraction. a_i = estimate of the fraction of gas i volume used in processes with emission control technologies (site-specific), fraction, as determined in equation 6.8 d_i = Destruction Removal Efficiency (DRE) for gas i , fraction. UT = average uptime of all abatement systems, fraction, calculated per Equation 6.8.

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EQUATION 6.8 (NEW)
ESTIMATE OF THE FRACTION OF GAS I VOLUME IN PROCESSES WITH EMISSION CONTROL
TECHNOLOGIES

$$a_i = \left(\frac{n_a + \gamma \bullet m_a}{n + \gamma \bullet m} \right)$$

Where:

a_i = estimate of the fraction of gas i volume used in processes with suitable emission control technologies.

n_a = number of etch and wafer cleaning tools equipped with suitable abatement technology (site-specific).

m_a = number of TFD tools equipped with suitable abatement technology (site-specific).

n = total number of etch and wafer cleaning tools (site-specific).

m = total number of TFD tools (site-specific).

γ = factor reflecting the ratio of the uncontrolled emissions of gas i from TFD tools to the uncontrolled emissions of gas i from etch and wafer cleaning tools.

EQUATION 6.9 (NEW)
UPTIME OF EMISSIONS CONTROL SYSTEMS

$$UT = 1 - \frac{\sum_n Td_n}{\sum_n UT_n}$$

Where:

UT = average uptime factor of all abatement systems connected to process tools, fraction.

Td_n = The total time, in minutes, that abatement system n connected to process tool(s) in the plant, is not in operational mode when at least one of the manufacturing tools connected to abatement system n is in operation.

UT_n = total time, in minutes per year, in which abatement system n has at least one associated manufacturing tool in operation. For determining the amount of tool operating time, you may assume that tools that were installed for the whole of the year were operated for 525,600 minutes per year. For tools that were installed or uninstalled during the year, you should prorate the operating time to account for the days in which the tool was not installed; treat any partial day that a tool was installed as a full day (1,440 minutes) of tool operation. For an abatement system that has more than one connected tool, the tool operating time is 525,600 minutes per year if at least one tool was installed at all times throughout the year. If you have tools that are idle with no gas flow through the tool for part of the year, you may calculate total tool time using the actual time that gas is flowing through the tool. *Nota bene:* UT may be set to 1 if suitable backup abatement or interlocking with the process tool is implemented for each abatement system.

n = abatement system.

TIER 2B METHOD

The Tier 2b method uses the same set of equations as the Tier 2a method (Equations 6.2 to 6.13), but distinct emission factors are provided depending on the substrate size being manufactured ($\leq 200\text{mm}$ vs. $\geq 300\text{mm}$ for semiconductor, see {Table 6.7}). As discussed in section 6.2.1, the use of the Tier 2b method over the Tier 2a is preferred, unless it is not possible to distinguish gas consumption by substrate size (for manufacturing facilities that process multiple substrate sizes). Hence, for facilities that manufacture only one size of substrates ($\leq 200\text{mm}$ or $\geq 300\text{mm}$ for the semiconductor sub-sector), the corresponding U_i and $B_{k,i}$ default emissions factors should be used ($BP = CF_4, C_2F_6, CHF_3, C_3F_8, C_4F_6, C_4F_8, C_5F_8, CH_3F$ and CH_2F_2). With this distinction in mind, all other Tier 2b variables ($h_i, C_i, D_i, a_i, d_i, UT, Td_n$, and UT_n) are estimated in the same manner as for the Tier 2a method. Similarly, total Tier 2b emissions are equal to the sum of emissions from all gases i used in the production process

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(E_i) plus the emissions of by-products (BPE_{CF4,i}, BPE_{C2F6,i}, BPE_{CHF3,i}, BPE_{C3F8,i}, BPE_{C4F6,i}, BPE_{C4F8,i}, BPE_{C5F8,i}, BPE_{CH3F,i}, and BPE_{CH2F2,i}) resulting from the conversion of all gases *i* used during production, as calculated using Equations 6.2, to 6.14.

TIER 2C METHOD

The Tier 2c method is based on a set of equations allowing to account for default emission factors that are provided for distinct substrate sizes ($\leq 200\text{mm}$ or $\geq 300\text{mm}$ for the semiconductor sub-sector) and for distinct process types 'p'. In the Tier 2c method, there are 6 process types defined as 1) etching and wafer cleaning, 2) remote plasma cleaning, 3) in-situ plasma cleaning, 4) in-situ thermal cleaning, 5) N₂O TFD, and 6) N₂O 'other'.

Please see Tables 6.11 to 6.12 for the default Tier 2c emission factors for the semiconductor sub-sector ($\leq 200\text{mm}$ and $\geq 300\text{mm}$ wafer sizes respectively).

As discussed in section 6.2.1, the use of the Tier 2c method is preferred over the Tier 2a or Tier 2b methods because the Tier 2c default emission factors are more accurate than the Tier 2b or 2a factors. However, using the Tier 2c method requires apportioning gas consumption by process type, which introduces additional complexity. Please see the guidance for apportioning gas usage for further detail. As for the Tier 2a and 2b methods, the Tier 3b total emissions are equal to the sum of emissions from all unreacted gases *i* used in the production process (E_i) plus the emissions of all by-products *k* (BPE_k) resulting from the conversion of all gases *i* used during production, but such emissions are calculated using process-type-dependent Equations 6.10 and 6.11 as shown below:

EQUATION 6.10 (UPDATED) EMISSION OF INPUT GAS I

$$E_i = (1 - h_i) \cdot \Sigma_p [C_{i,p} \cdot (1 - U_{i,p}) \cdot (1 - D_{i,p})]$$

Where:

E_i = emissions of unreacted input gas *i*, kg.

h_i = fraction of input gas *i* remaining in shipping container (heel) after use, fraction.

C_{i,p} = consumption of input gas *i* (*i* = CF₄, C₂F₆, C₃F₈, C₄F₆, c-C₄F₈, C₅F₈, c-C₄F₈O, CHF₃, CH₂F₂, CH₃F, C₂H₅F, COF₂, F₂, N₂O, NF₃, SF₆), for process type *p*, kg.

U_{i,p} = use rate of input gas *i* (fraction destroyed or transformed in process) for process type *p*, fraction.

D_{i,p} = Overall reduction of input gas *i* emissions for process type *p*, fraction, calculated per Equation 6.12.

p = process type.

EQUATION 6.11 (UPDATED) BY-PRODUCT EMISSIONS

$$BPE_k = \Sigma_i [(1 - h_i) \cdot [\Sigma_p [B_{k,i,p} \cdot C_{i,p} \cdot (1 - D_{k,p})] + C_{i,p} \cdot AB_{i,CF4}]$$

Where:

BPE_k = emissions of by-product *k* generated from the conversion of all input gases *i* for all process types *p*, kg.

h_i = fraction of input gas *i* remaining in shipping container (heel) after use, fraction.

B_{k,i,p} = emission factor, kg gas *k* created/kg input gas *i* used for process type *p*.

C_{i,p} = consumption of input gas *i* (*i* = CF₄, C₂F₆, C₃F₈, C₄F₆, c-C₄F₈, C₅F₈, c-C₄F₈O, CHF₃, CH₂F₂, CH₃F, C₂H₅F, COF₂, F₂, N₂O, NF₃, SF₆), for process type *p*, kg.

D_{k,p} = overall reduction of gas *k* by-product emissions for process type *p*, fraction, calculated per Equation 6.12 (replacing *i* by *k* indexes).

AB_{i,CF4} = Fraction of NF₃ in process exhaust gas that is converted into CF₄ by direct reaction with hydrocarbon fuel and F₂ gas in a combustion abatement system. *AB_{F2,CF4}* = Fraction of F₂ in process exhaust gas that is converted into CF₄ by direct reaction with hydrocarbon fuel gas in a combustion abatement system. These are set to zero if the abatement OEM or electronics manufacturer can certify that the rate of conversion is <0.1%, otherwise use a default value, e.g. 0.093 kg CF₄ per kg NF₃ and 0.116 kg CF₄ per kg F₂. This will be taken into account in calculations in Tiers 2 & 3.

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p = process type.

EQUATION 6.12 (ELABORATION)**EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL TECHNOLOGY**

$$D_{i,p} = a_{i,p} \cdot d_{i,p} \cdot UT_p$$

Where:

$D_{i,p}$ = overall reduction of gas i emissions for process type p , fraction.

$a_{i,p}$ = fraction of gas i volume fed into process type p with emission control technologies (site specific), fraction. Unlike in the Tier 2a and Tier 2b methods, where a_i is calculated based on the number of tools and on a γ factor reflecting an average difference in uncontrolled emissions between types of tools, the $a_{i,p}$ factor for the Tier 2c method is to be calculated based on the estimated volume of gas i emitted from each process p . Such volume of gas may be estimated from the Tier 2c calculation itself (using the default $U_{i,p}$ and $B_{k,i,p}$ Tier 2c default emission factors).

$d_{i,p}$ = Destruction Removal Efficiency (DRE) for gas i and process type p , fraction.

UT_p = average uptime of all abatement systems connected to tools running process type p , fraction, calculated per Equation 6.13.

EQUATION 6.13 (NEW)**UPTIME OF EMISSIONS CONTROL SYSTEMS**

$$UT_p = 1 - \frac{\sum_n Td_{n,p}}{\sum_n UT_{n,p}}$$

Where:

UT_p = average uptime factor of all abatement systems connected to process tools running process type p , fraction.

$Td_{n,p}$ = The total time, in minutes, that abatement system n connected to process tools running process type p in the plant, is not in operational mode when at least one of the manufacturing tools connected to abatement system n is in operation.

$UT_{n,p}$ = total time, in minutes per year, in which abatement system n has at least one associated manufacturing tool running process type p in operation. For determining the amount of tool operating time, you may assume that tools that were installed for the whole of the year were operated for 525,600 minutes per year. For tools that were installed or uninstalled during the year, you should prorate the operating time to account for the days in which the tool was not installed; treat any partial day that a tool was installed as a full day (1,440 minutes) of tool operation. For an abatement system that has more than one connected tool, the tool operating time is 525,600 minutes per year if at least one tool was installed at all times throughout the year. If you have tools that are idle with no gas flow through the tool for part of the year, you may calculate total tool time using the actual time that gas is flowing through the tool. *Nota bene:* UT may be set to 1 if suitable backup abatement or interlocking with the process tool is implemented for each abatement system.

n = abatement system.

p = process type.

ADAPTING TIER 2 METHODS TO ACCOUNT FOR TECHNOLOGICAL CHANGES

Given the rapid pace of technological change in electronics manufacturing, Tier 2 default emission factors may need to be supplemented or updated in order to remain representative of industry emission rates. A change in any of the following parameters can result in the Tier 2 default emission factors becoming unrepresentative:

- Substrate size (e.g., moving to 450 mm wafers in semiconductor manufacturing);

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- Use of a new gas in an existing process type/subtype (i.e., thin film chamber clean process, in-situ plasma, remote plasma, or thermal subtype; plasma etch process; thin film deposition process) or use of a new process type;
- Film type introduced after 2018;
- Tool platform introduced by a supplier after 2018 or those introduced earlier but used for a new process type/subtype;
- Use of new input process greenhouse gases (e.g., use of a carbon containing F-GHG for 300mm in-situ plasma chamber cleaning), use of new combinations of process greenhouse gases, or use of low- or no-GWP materials that have the potential to form GHG byproducts.

If default emission factors are not available under Tier 2 (e.g., a new gas or process type/subtype is introduced), and when the use of the input gas(es) does not result in the formation of greenhouse gases as process byproducts (e.g. formation of CF₄ from F₂, COF₂ chamber cleaning or from CF₃I-based etch processes), facilities can estimate emissions using Tier 2 and assume a default emission factor (1-U) = 0.8 with by-product emission factors of 0.1 for both CF₄ and C₂F₆. Alternatively, facilities can undertake process emissions characterization under Tier 3a and use a hybrid method.

It is good practice for inventory compilers to work with electronics manufacturers to periodically assess whether Tier 2 defaults remain representative of manufacturing conditions, considering the criteria above. If the Tier 2 defaults are found not to be representative in one or more respects, inventory compilers should work with electronics manufacturers to encourage use of hybrid Tier 2 and Tier 3a methods, or to develop country-specific default emission factors that reflect the applicable technological and process changes cited above. A hybrid method would involve applying the Tier 2 defaults to processes and technologies that have not changed while applying Tier 3a, site-specific emission factors to processes and technologies that have changed.

Figure 6.2. Decision tree to determine need for measured emission factors, should be used to determine when Tier 3a measured emission factors may be necessary to supplement Tier 2 default emission factors.

In the case where a new substrate size will be used in a facility (e.g., 450-mm wafers), emission factors may be measured and applied in phases. For example, in the first year of operation of the 450-mm fab, 300mm Tier 2c default factors could be used to estimate emissions. In subsequent years, Tier 2 defaults should be used to estimate emissions for up to 50% of total gas used in year 2; 25% in year 3; 10% in year 4; and 0% in year 5. See the discussion of the Tier 3a method below for criteria to prioritize these measurements. Once measurements of the 450-mm processes are complete, inventory compilers should work with semiconductor manufacturers to recalculate emissions from years 1-4 to ensure time series consistency.

TIER 3 METHODS – SITE-SPECIFIC PARAMETERS

TIER 3A MEASURED PARAMETERS

The Tier 3a method uses the same set of equations as the Tier 2c method; however, Tier 3a uses measured values for parameters in equations 6.7 to 6.10. As discussed above, Tier 3a measured emission factors may be used to supplement Tier 2 default factors where some, but not all, processes and technologies have changed. Tier 3a can also be undertaken to develop facility-specific emission factors for broader application in the fab. (Note that in the case of a comprehensive technology change, such as the adoption of a new substrate size (e.g., 450mm in semiconductor industry), the Tier 3a method would be broadly applied.)

The (1-U) and BPE emission factors in Equations 6.7-6.10 are measured for ‘recipes’, i.e., specific combinations of process conditions (e.g. gas flows, plasma power, pressure, temperature, duration) and technologies used to etch patterns onto electronics devices, to clean film deposition chambers, or to deposit films on substrate) or for sets of ‘similar’ recipes. A centreline recipe can be used to establish Tier 3a emission factors for each set of similar recipes. Recipes are deemed ‘similar’ when the centreline process can reasonably be deemed representative of facility-specific process conditions, of the potential variability of such process conditions around the centreline process during normal manufacturing operations, and when the substrate size, process type/subtype, tool platform, film type (e.g. SiO_xNy, Si_xNy), and input process gases are the same. However, even when similar recipes are grouped, it may not be practicable or economically feasible to implement the Tier 3a methodology across all families of similar recipes or across the many abatement systems that may be used in a particular electronics manufacturing facility. For this reason, it is good practice for fabs undertaking a more comprehensive Tier 3a approach to prioritize testing as follows:

1. Recipe families with highest GHG usage (e.g., chamber cleans) and/or expected emissions should be tested first (e.g., testing should account for top 75% of total process greenhouse gas usage in kg and the top 50% of emissions in kg CO₂e.);

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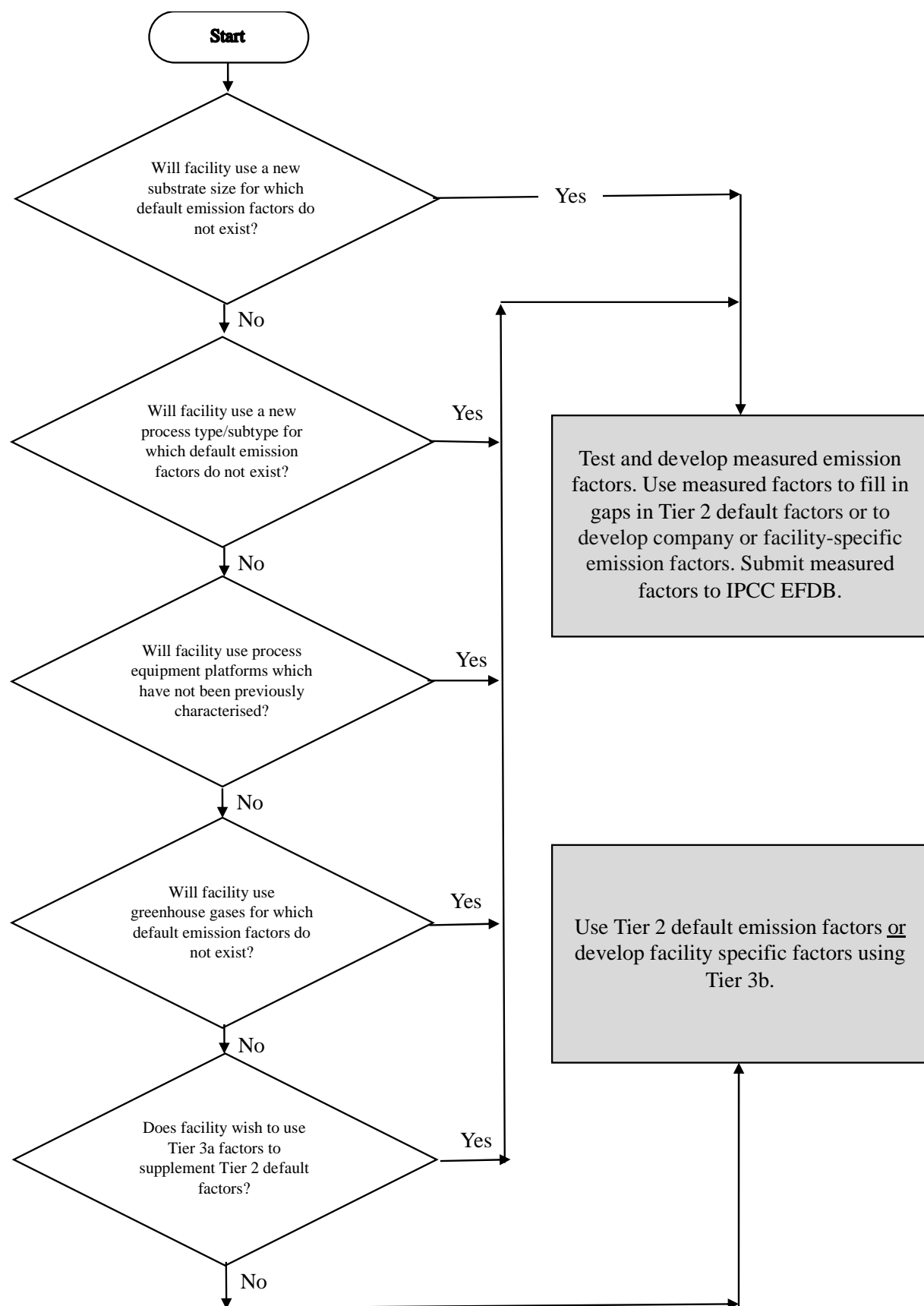
2. Stable processes which do not change from wafer to wafer or run to run should have higher priority than processes that change frequently.

Whenever Tier 3 measurements are made, the reporting facility should document the following:

- Date measurements were made;
- Fab type;
- Substrate size;
- Process type;
- Film type;
- Tool manufacturer, platform and model/chamber name;
- Process conditions;
- Input gases;
- Input gas emission factors;
- Byproduct emission factors;
- Fluorine mass balance closure;
- Measurement protocol used.

In addition, facilities using the 3a approach should document all facility-specific process or abatement emission factors that have been measured by the reporting facility(ies), document which recipes are deemed similar to the measured centreline process, use the measured Tier 3a factors for all similar recipes, and be able to demonstrate to a reasonable degree of certainty that the Tier 3a approach does lead to increased accuracy in reporting emissions. When facility-specific emission factors or destruction removal efficiencies have been measured for a particular recipe or for a family of similar recipes and for a particular abatement technology or abatement system, it is NOT good practice to revert to default Tier 2 emission factors when such default emission factors are more favourable than the corresponding measured Tier 3a factors, as such practice would result in knowingly underestimating emissions.

Tier 3a measured emission factors and supporting data should be submitted to the IPCC Emission Factor Database (EFDB). Countries in which measured data is collected should examine the data against criteria to determine if adequate data has been collected to develop new Tier 2 default factors or revise existing factors.

Figure 6.2 (new) Decision tree to determine need for measured emission factors

TIER 3B METHOD

Stack testing measures the amount of regulated pollutants or surrogates emitted from a specific facility. It is a method commonly used by semiconductor fabs to quantify emissions and demonstrate compliance for regulated pollutants used in semiconductor manufacturing, such as acid gases (e.g., hydrogen fluoride, hydrogen chloride, fluorine, nitric acid, ammonia) and volatile organic compounds. The individual plasma etch and chamber clean operations that use process greenhouse gases, as is the case with acid gases and VOCs, are conducted as batch processes. The fact that they are run concurrently, in rapid succession on a large number of tools which are exhausted to typically a relatively small number of stacks, leads to the expectation that the emissions will largely emulate a continuous process.

The analytical methods available for measuring fluorinated greenhouse gas emissions from factory stacks are Fourier Transform Infrared spectroscopy (FTIR) and gas chromatography followed by mass spectrometry (GC/MS). In the case of FTIR the analytical instrument is brought to the stack for in-situ analysis while, in the case of the GC/MS approach, stack emission samples are collected using sample containers and transported to a laboratory for analysis.

Stack testing may be used to develop fab specific emission factors. The stack method may not be appropriate for fabs with many stacks, frequent changes in production technology or product mix, or an inability to track gas use during testing or abatement uptime during testing. It is also important to perform stack testing when production levels in the fab are representative of year-round production, and when abatement system uptime is representative of year-round uptime.

Ranking Stacks for Testing

It is *good practice* to test as many stacks as practicable, including the highest-emitting stacks that cumulatively represent a minimum of 85% of total fab CO₂e emissions. (Equations 6.18 and 6.19 include a factor θ , which is based on the results of Equations 6.14 and 6.15, to account for emissions from any untested stacks.) To rank stacks by their expected contribution to total emissions, use equations 6.14 and 6.15 along with the default emissions factors found in the Tier 2a or 2b method (depending upon whether more than one wafer size is manufactured by the fab). Consumption data from the previous year may be used for this preliminary estimate.

EQUATION 6.13 (NEW)
PRELIMINARY ESTIMATE OF STACK PROCESS GAS EMISSIONS

$$E_{ij} = C_{ij} \cdot (1 - U_{ij}) \cdot (1 - (a_{ij} \cdot D_{ij} \cdot UT_j)) \cdot CF \cdot 0.001$$

Where:

E_{ij} = Annual emissions of input gas i from stack system j, on a fab basis (metric tons CO₂e).

C_{ij} = Amount of input gas i consumed for stack system j (kg), (expressed as ratio of tools connected to stack j using gas i/total number of tools in fab using gas i).

U_{ij} = Process utilization rate for input gas i for stack system j, (expressed as a decimal fraction).

a_{ij} = estimate of the fraction of gas i volume used in processes with emission control technologies (site-specific), fraction, as determined in equation 6.8).

D_{ij} = Fraction of input gas i destroyed or removed in abatement systems connected to process tools that are vented to stack system j (expressed as a decimal fraction).

UT_j = The average uptime factor of all abatement systems connected to process tools (expressed as a decimal fraction).

0.001 = Conversion factor from kg to metric tons.

CF - Conversion factor to calculate emission estimates in CO₂ equivalent unit (*the same conversion factors should be used as those used for key category analysis, see Chapter 4, Volume 1*).

i = Input gas.

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j = Stack system.

EQUATION 6.15 (NEW)

PRELIMINARY ESTIMATE OF BYPRODUCT EMISSIONS FROM STACKS

$$BE_{ijk} = B_{ijk} \cdot C_{ij} \cdot (1 - (a_{ij} \cdot D_{jk} \cdot UT_{ijk})) \cdot CF \cdot 0.001$$

Where:

BE_{ijk} = Annual emissions of by-product gas k formed from input gas i for stack system j (metric tons).

B_{ijk} = By-product formation rate of gas k created as a by-product per amount of input gas i (kg) consumed by tools connected to stack system j (kg).

C_{ij} = Amount of input gas i consumed for stack system j, (expressed as ratio of tools connected to stack j using gas i/total number of tools in fab using gas i) (kg).

a_{ij} = estimate of the fraction of gas i volume used in processes with emission control technologies (site-specific), fraction, as determined in equation 6.8.

D_{jk} = Fraction of by-product gas k destroyed or removed in abatement systems connected to stack j (expressed as a decimal fraction).

UT_{ijk} = The average uptime factor of all abatement systems connected to process tools in the fab (expressed as a decimal fraction)

CF - Conversion factor to calculate emission estimates in CO₂e equivalent unit (*the same conversion factors should be used as those used for key category analysis, see Chapter 4, Volume 1*).

0.001 = Conversion factor from kg to metric tons.

i = Input gas.

j = Stack system.

k = By-product gas.

Testing Frequency

Fabs which use the stack test option should test major F-gas emitting stacks annually. If a company determines that no substantive changes have occurred in the year following a stack test, the emission factors determined may remain unchanged and retesting is not required; however, stack testing should occur every 3 years at a minimum. Fabs with a highly variable product mix should consider undertaking annual testing for the first three years to assess the impact that the changing product mix has on their measured emission factors. For all fabs, the following are considered to be substantive changes, and testing should be undertaken in the subsequent year after a stack test if any of the following are met:

(i) Annual consumption of a fluorinated GHG used during the most recent emissions test (expressed in CO₂e) changes by more than 10 percent of the total annual fluorinated GHG consumption, relative to gas consumption in CO₂e for that gas during the year of the most recent emissions test (for example, if the use of a single gas goes from 25 percent of total gas consumption to greater than 35 percent of total gas consumption, this change would trigger a re-test).

(ii) A change in the consumption of a GHG that was not used during the emissions test and not reflected in the fab-specific emission factor

(iii) A decrease by more than 20 percent in the fraction of tools with abatement systems, compared to the number during the most recent emissions test.

(iv) A change in the wafer size manufactured by the fab since the most recent emissions test.

(v) A stack system that formerly met the criteria specified for not being subject to testing no longer meets those criteria.

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Stack test method

For each stack system in the fab for which testing is required, measure the emissions of each fluorinated GHG from the stack system by conducting an emission test. In addition, measure the fab-specific consumption of each fluorinated GHG. Measure emissions and consumption of each fluorinated GHG according to the following criteria:

- Measure total gas flow rate up the stack on the test day using EPA Method 1 or 2 or an equivalent method.
- Measure process GHG concentrations of designated gases from relevant stacks using an analytical method with demonstrated accuracy. Validate the analytical method using EPA Method 320 or alternate validation method.
- Emissions testing should be conducted during a period of 8 hours or longer per stack system while the fab is operating at a representative level with representative abatement system uptime.
- Measurements should be taken for fluorinated gases known to be used by the fab and any possible fluorinated greenhouse gas byproducts. If an expected byproduct or known used gas is not detected, use ½ the FDL. CF₄, C₂F₆, CHF₃, CH₂F₂, and CH₃F are expected byproducts. C₃F₈, C₄F₆, c-C₄F₈, C₅F₈ are possible additional by-products. Make measurements for all nine possible by-products.
- If a gas is added to use in the fab at a time after stack testing is conducted, then emissions should be estimated per one of the other methods described in this chapter (Tiers 2a, 2b, 2c) for the reporting year.
- Determine the amount of each fluorinated GHG consumed by each fab during the sampling period. Where starting and ending pressures are used to estimate consumption, make appropriate adjustments for temperature and deviations from ideal gas law behavior (e.g., by applying the Redlich, Kwong, Soave equation of state with appropriate values for each F-GHG).
- If consumption of a fluorinated GHG is too low to be accurately measured during the testing period, then either increase the testing period in order to account for usage or calculate consumption from pro-rated long-term consumption data.

Calculating Emissions

Calculate the emissions of each fluorinated GHG consumed as an input gas using Equation 6.16 and each fluorinated GHG formed as a by-product gas using Equation 6.17. If a stack system is comprised of multiple stacks, you should sum the emissions from each stack in the stack system when using Equation 6.16 or Equation 6.17 of this section.

EQUATION 6.16 (NEW)
TOTAL FLUORINATED GHG INPUT GAS EMITTED FROM STACK SYSTEM DURING SAMPLING PERIOD

$$E_{is} = MW_i \cdot Q_s \cdot \frac{1}{SV} \cdot \frac{1}{10^3} \cdot \sum_{M=1}^N \frac{X_{ism}}{10^9} \cdot \Delta t_m$$

Where:

E_{is} = Total fluorinated GHG input gas i, emitted from stack system s, during the sampling period (kg).

X_{ism} = Average concentration of fluorinated GHG input gas i in stack system s, during the time interval m (ppbv).

MW_i = Molecular weight of fluorinated GHG input gas i (g/g-mole).

Q_s = Flow rate of the stack system s, during the sampling period (m³/min).

SV = Standard molar volume of gas (0.0240 m³/g-mole at 68°F and 1 atm).

Δt_m = Length of time interval m (minutes). Each time interval in the FTIR sampling period should be less than or equal to 60 minutes (for example an 8 hour sampling period would consist of at least 8 time intervals).

$1/10^3$ = Conversion factor (1 kilogram/1,000 grams).

i = Fluorinated GHG input gas.

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918 s = Stack system.
 919 N = Total number of time intervals m in sampling period.
 920 m = Time interval.

EQUATION 6.17 (NEW)
TOTAL FLUORINATED GHG BY-PRODUCT GAS EMITTED FROM STACK SYSTEM DURING
SAMPLING PERIOD

$$E_{ks} = MW_k \cdot Q_s \cdot \frac{1}{SV} \cdot \frac{1}{10^3} \cdot \sum_{M=1}^N \frac{X_{ksm}}{10^9} \cdot \Delta t_m$$

927 Where:

928 E_{ks} = Total fluorinated GHG by-product gas k , emitted from stack system s , during the sampling period
 929 (kg).

930 X_{ks} = Average concentration of fluorinated GHG by-product gas k in stack system s , during the time interval
 931 m (ppbv).

932 MW_k = Molecular weight of the fluorinated GHG by-product gas k (g/g-mole).

933 Q_s = Flow rate of the stack system s , during the sampling period (m³/min).

934 SV = Standard molar volume of gas (0.0240 m³/g-mole at 68 °F and 1 atm).

935 Δt_m = Length of time interval m (minutes). Each time interval in the FTIR sampling period should be less
 936 than or equal to 60 minutes (for example an 8 hour sampling period would consist of at least 8 time
 937 intervals).

938 $1/10^3$ = Conversion factor (1 kilogram/1,000 grams).

939 k = Fluorinated GHG by-product gas.

940 s = Stack system.

941 N = Total number of time intervals m in sampling period.

942 m = Time interval.

943
 944 When calculating emissions from the stack testing results use the following guidelines and the accompanying
 945 requirements in Tables 6.3M, 6.3N, and 6.3O:

- 946 a. If a fluorinated GHG is consumed during the sampling period, but emissions are not detected, use one-
 947 half of the field detection limit you determined for that fluorinated GHG for the value of “ X_{ism} ” in
 948 Equation 6.16 or X_{ksm} in Equation 6.17.
- 949 b. If a fluorinated GHG is consumed during the sampling period and detected intermittently during the
 950 sampling period, use the detected concentration for the value of “ X_{ism} ” in Equation 6.16 when available
 951 and use one-half of the field detection limit you determined for that fluorinated GHG for the value of
 952 “ X_{ism} ” when the fluorinated GHG is not detected.
- 953 c. If a fluorinated GHG is not consumed during the sampling period and is an expected by-product gas and
 954 is not detected during the sampling period, use one-half of the field detection limit you determined for
 955 that fluorinated GHG for the value of “ X_{ksm} ” in Equation 6.17.
- 956 d. If a fluorinated GHG is not consumed during the sampling period and is a possible by-product gas as
 957 listed in Table I-17 of this section, and is not detected during the sampling period, then assume zero
 958 emissions for that fluorinated GHG for the tested stack system.

959 Calculate a fab-specific emission factor for each fluorinated GHG input gas consumed (in kg of fluorinated GHG
 960 emitted per kg of input gas i consumed) in the tools that vent to stack systems that are tested, as applicable, using
 961 Equation 6.18 of this section. If the emissions of input gas i exceed the consumption of input gas i during the
 962 sampling period, then equate “ E_{is} ” to the consumption of input gas i and treat the difference between the emissions
 963 and consumption of input gas i as a by-product of the other input gases, using Equation 6.19 of this section.

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EQUATION 6.18 (NEW)
GAS SPECIFIC EMISSION FACTOR

$$EF_{if} = \frac{(\sum_s E_{is}) \cdot \frac{1}{\theta}}{Activity_{if} \cdot (UT_f + (\frac{1 - UT_f}{1 - (a_{if} \cdot d_{if})}))}$$

Where:

EF_{if} = Emission factor for fluorinated GHG input gas i, from fab f, representing 100 percent abatement system uptime (kg emitted/kg input gas consumed).

E_{is} = Mass emission of fluorinated GHG input gas i from stack system s, during the sampling period (kg emitted).

θ = fraction of total fab emissions included in the tested stacks based on preliminary estimates

$Activity_{if}$ = Consumption of fluorinated GHG input gas i, for fab f during the stack testing period

UT_f = The total uptime of all abatement systems for fab f, during the sampling period, as calculated in Equation 6.23 of this section (expressed as decimal fraction). If the stack system does not have abatement systems on the tools vented to the stack system, the value of this parameter is zero.

a_{if} = ratio of tools with abatement systems versus tools without abatement systems for fluorinated GHG input gas i used in fab f (expressed as a decimal fraction).

d_{if} = Fraction of fluorinated GHG input gas i destroyed or removed in abatement systems connected to process tools in fab f, as calculated in Equation 6.20 of this section (expressed as decimal fraction). If the stack system does not have abatement systems on the tools vented to the stack system, the value of this parameter is zero.

f = Fab.

i = Fluorinated GHG input gas.

s = Stack system.

Calculate a fab-specific emission factor for each fluorinated GHG formed as a by-product (in kg of fluorinated GHG per kg of total fluorinated GHG consumed) in the tools vented to stack systems that are tested, as applicable, using Equation 6.19 of this section. When calculating the by-product emission factor for an input gas for which emissions exceeded its consumption, exclude the consumption of that input gas from the term " $\sum(Activity_{if})$."

EQUATION 6.19 (NEW)
GAS SPECIFIC BY-PRODUCT EMISSION FACTOR

$$EF_{kf} = \frac{(\sum_s E_{ks}) \cdot \frac{1}{\theta}}{\sum_i Activity_{if} \cdot (UT_f + (\frac{1 - UT_f}{1 - (a_f \cdot d_{kf})}))}$$

Where:

EF_{kf} = Emission factor for fluorinated GHG by-product gas k, from fab f, representing 100 percent abatement system uptime (kg emitted/kg of all input gases consumed in tools vented to stack systems that are tested).

E_{ks} = Mass emission of fluorinated GHG by-product gas k, emitted from stack system s, during the sampling period (kg emitted).

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- θ = fraction of total fab emissions included in the tested stacks based on preliminary estimates
- $Activity_{if}$ = Consumption of fluorinated GHG input gas i for fab f during the stack testing period
- UT_f = The total uptime of all abatement systems for fab f , during the sampling period, as calculated in Equation 6.23 of this section (expressed as decimal fraction).
- a_f = ratio of tools with abatement systems versus without abatement systems for input gas i of all fluorinated input gases used in fab f
- d_{kf} = Fraction of fluorinated GHG by-product gas k destroyed or removed in abatement systems connected to process tools in fab f , as calculated in Equation 6.20 of this section (expressed as decimal fraction).
- f = Fab.
- i = Fluorinated GHG input gas.
- k = Fluorinated GHG by-product gas.
- s = Stack system.

EQUATION 6.20 (NEW)
AVERAGE WEIGHTED FRACTION OF GREENHOUSE INPUT GAS AND BYPRODUCT GAS

$$d_{if} = \frac{\sum_j [C_{ijf} \cdot (1 - U_{ij}) \cdot DRE_{ij}]}{\sum_j [C_{ijf} \cdot (1 - U_{ij})]}$$

$$d_{kf} = \frac{\sum_j [C_{ijf} \cdot (B_{ijk}) \cdot DRE_{jk}]}{\sum_j [C_{ijf} \cdot (B_{ijk})]}$$

Where:

- d_{if} = The average weighted fraction of fluorinated GHG input gas i destroyed or removed in abatement systems in fab f (expressed as a decimal fraction).
- d_{kf} = The average weighted fraction of fluorinated GHG by-product gas k destroyed or removed in abatement systems in fab f (expressed as a decimal fraction).
- C_{ijf} = The amount of fluorinated GHG input gas i consumed for process type or sub-type j fed into abatement systems in fab f (kg).
- $(1 - U_{ij})$ = The default emission factor for input gas i used in process type or sub-type j , from applicable Tables I-3 through I-7 of this section.
- B_{ijk} = The default by-product gas formation rate factor for by-product gas k from input gas i used in process type or sub-type j , from applicable Tables I-3 through I-7 of this section.
- DRE_{ij} = Destruction or removal efficiency for fluorinated GHG input gas i in abatement systems connected to process tools where process type or sub-type j is used (expressed as a decimal fraction)
- DRE_{jk} = Destruction or removal efficiency for fluorinated GHG by-product gas k in abatement systems connected to process tools where input gas i is used in process type or sub-type j (expressed as a decimal fraction)
- f = fab.
- i = Fluorinated GHG input gas.
- j = Process type or sub-type.

Calculate annual fab-level emissions of each fluorinated GHG consumed using Equation 6.21 of this section.

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EQUATION 6.21 (NEW)
ANNUAL EMISSIONS OF FLUORINATED GHG

$$E_{if} = EF_{if} \bullet c_{if} \bullet UT_f + \frac{EF_{if}}{(1 - (a_{if} \bullet d_{if}))} \bullet c_{if} \bullet (1 - UT_f)$$

Where:

E_{if} = Annual emissions of fluorinated GHG input gas i (kg/year) from the stack systems that are tested for fab f.

EF_{if} = Emission factor for fluorinated GHG input gas i emitted from fab f, as calculated in Equation 6.18 of this section (kg emitted/kg input gas consumed).

C_{if} = Total consumption of fluorinated GHG input gas i, for fab f, for the reporting year (kg/year).

UT_f = The total uptime of all abatement systems for fab f, during the reporting year, as calculated using Equation 6.23 of this section (expressed as a decimal fraction).

a_{if} = estimate of the fraction of gas i volume used in processes with emission control technologies (site-specific), fraction, as determined in equation 6.8.

d_{if} = Fraction of fluorinated GHG input gas i destroyed or removed in abatement systems connected to process tools in fab f that are included in the stack testing option, as calculated in Equation 6.20 of this section (expressed as decimal fraction).

f = Fab.

i = Fluorinated GHG input gas.

Calculate annual fab-level emissions of each fluorinated GHG by-product formed using Equation 6.22 of this section.

EQUATION 6.22 (NEW)
ANNUAL EMISSIONS OF FLUORINATED GHG BY-PRODUCT

$$E_{kf} = EF_{kf} \bullet \sum_i c_{if} \bullet UT_f + \frac{EF_{kf}}{(1 - (a_f \bullet d_{kf}))} \bullet c_{if} \bullet (1 - UT_f)$$

Where:

E_{kf} = Annual emissions of fluorinated GHG by-product k (kg/year) from the stack systems that are tested for fab f.

EF_{kf} = Emission factor for fluorinated GHG by-product k, emitted from fab f, as calculated in Equation 6.19 of this section (kg emitted/kg of all fluorinated input gases consumed).

C_{if} = Total consumption of fluorinated GHG input gas i, for fab f, for the reporting year

UT_f = The total uptime of all abatement systems for fab f, during the reporting year as calculated using Equation 6.23 of this section (expressed as a decimal fraction).

a_f = estimate of the fraction of gas i volume used in processes with emission control technologies (site-specific), fraction, as determined in equation 6.8

d_{kf} = Fraction of fluorinated GHG by-product k destroyed or removed in abatement systems connected to process tools in fab f that are included in the stack testing option, as calculated in Equation 6.21 of this section (expressed as decimal fraction).

f = Fab.

i = Fluorinated GHG input gas.

k = Fluorinated GHG by-product

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When using the stack testing method, calculate abatement system uptime on a fab basis using Equation 6.23 of this section. When calculating abatement system uptime for use in Equation 6.18 and 6.19 of this section, you should evaluate the variables “ T_{dpf} ” and “ UT_{pf} ” for the sampling period instead of the reporting year. Abatement system uptime, UT_f can be simplified to 1 if abatement systems being tested have interlocks with tool runtime. If interlocked abatement systems have a margin of error (tools can finish their current wafer lot, then companies can determine if a more applicable value is appropriate). Company records such as maintenance records for abatement systems can also be used to estimate abatement system uptime.

EQUATION 6.23 (NEW)
AVERAGE ABATEMENT SYSTEM UPTIME

$$UT_f = 1 - \frac{\sum_p T_{dpf}}{\sum_p UT_{pf}}$$

Where:

UT_f = The average uptime factor for all abatement systems in fab f (expressed as a decimal fraction).

T_{dpf} = The total time, in minutes, that abatement system p , connected to process tool(s) in fab f , is not in operational mode

UT_{pf} = Total time, in minutes per year, in which the tool(s) connected at any point during the year to abatement system p , in fab f could be in operation. For determining the amount of tool operating time, you may assume that tools that were installed for the whole of the year were operated for 525,600 minutes per year. For tools that were installed or uninstalled during the year, you should prorate the operating time to account for the days in which the tool was not installed; treat any partial day that a tool was installed as a full day (1,440 minutes) of tool operation. For an abatement system that has more than one connected tool, the tool operating time is 525,600 minutes per year if there was at least one tool installed at all times throughout the year. If you have tools that are idle with no gas flow through the tool, you may calculate total tool time using the actual time that gas is flowing through the tool.

f = Fab.

p = Abatement system.

6.2.1.2 HEAT TRANSFER FLUIDS

Liquid fluorinated compounds are used as heat transfer fluids (HTFs) for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of semiconductor manufacturing production processes. Leakage and evaporation of these fluids during use is a source of fluorinated gas emissions.

Unweighted HTF emissions consist primarily of perfluorinated amines, hydrofluoroethers, perfluoropolyethers, and perfluoroalkylmorpholines. With the exception of the hydrofluoroethers, all of these compounds are very long-lived in the atmosphere and have high GWPs (near 10,000). It should be noted that some lower GWP HTF materials may be regulated in some regions (e.g., as volatile organic compounds) and this should be considered when choosing alternative HTFs.

There are two methods for estimating emissions from the use of heat transfer fluids. The choice of methods will depend on the availability of activity data on the use of heat transfer fluids, and is outlined in the decision tree (see Figure 6.2, Decision Tree for Estimation of Emissions from Heat Transfer Fluids, and see Section 1.5 of Chapter 1, Choosing between the Mass Balance and Emission Factor Approach).

TIER 1 – HEAT TRANSFER FLUIDS

Tier 1 is appropriate when company-specific data are not available on heat transfer fluids (HTFs). It is the less accurate of the two methods for estimating emissions from losses of heat transfer fluids. The method, unlike the

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Tier 2 method, gives estimates of emissions for three HTFs that represent the three main types of compounds used as HTFs globally. For any class of electronic products (input material), the default emission factors are multiplied by the annual production (P, in units of square meters (m²)). The result is a set of annual emissions estimates expressed in kg of the gases emitted during the manufacture of that class of electronic products. The Tier 1 method for estimating emissions from liquid FCs is analogous to the Tier 1 method for estimating emissions from gaseous FCs during electronic devices manufacturing. The formula is shown in Equation 6.24.

EQUATION 6.24 (NEW)**TIER1 METHOD FOR ESTIMATION OF TOTAL FC EMISSIONS FROM HEAT TRANSFER FLUIDS**

$$FC_i = EF_i \cdot P$$

Where:

FC_i = Emissions of HTF i (kg)

EF_i = emission factor for HTF aggregate emissions per m² of substrate consumed during the period, (kg/m²)

P = annual production, m² of substrate used (surface area of substrate used during the production of electronic devices, including test substrates). If annual production is not available from an electronics producer, P may be calculated as the product of the annual manufacturing capacity and annual plant production capacity utilisation (fraction) of that producer.

TIER 2 METHOD – HEAT TRANSFER FLUIDS

There is one Tier 2 method for estimating actual emissions from the use of each FC fluid. This method is a mass-balance approach that accounts for liquid FC usage over an annual period. It is appropriate when company-specific data are available. Over the course of a year, liquid FCs are used to fill newly purchased equipment and to replace FC fluid loss from equipment operation through evaporation. The company should provide the chemical composition of the fluid(s) for which emissions are estimated.³ The method is expressed in Equation 6.25.

EQUATION 6.25 (UPDATED)**TIER2 METHOD FOR ESTIMATION OF FC EMISSIONS FROM HEAT TRANSFER FLUIDS**

$$FC_i = \rho_i \cdot (I_{it-1} + P_{it} - N_{it} + R_{it} - I_{it} - D_{it})$$

Where:

FC_i = Fluorinated heat transfer fluid emissions (kg).

ρ_i = density of liquid FC_i (kg/litre).

i = Fluorinated heat transfer fluid.

I_{it-1} = the inventory of liquid FC_i (litres) in containers other than equipment at the beginning of the reporting year (in stock or storage). The inventory at the beginning of the reporting year should be the same as the inventory at the end of the previous year.

P_{it} = Acquisitions of liquid FC_i during the reporting year, (litres) including amounts purchased from chemical suppliers, amounts purchased from equipment suppliers with or inside of equipment, and amounts returned to the facility after off-site recycling.

N_{it} = total nameplate capacity (full and proper charge) of equipment that uses fluorinated heat transfer fluid i and that is newly installed in the fab during the reporting year, (litres).

R_{it} = total nameplate capacity (full and proper charge) of equipment that uses fluorinated heat transfer fluid i and that is removed from service in the fab during the reporting year, (liters).

³ In the absence of GWP estimates, the appropriate GWP for C₆F₁₄ has been used as a proxy; see [http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR69v523/\\$File/05industrial.pdf](http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR69v523/$File/05industrial.pdf) at footnote to Table 4-58, page 166.

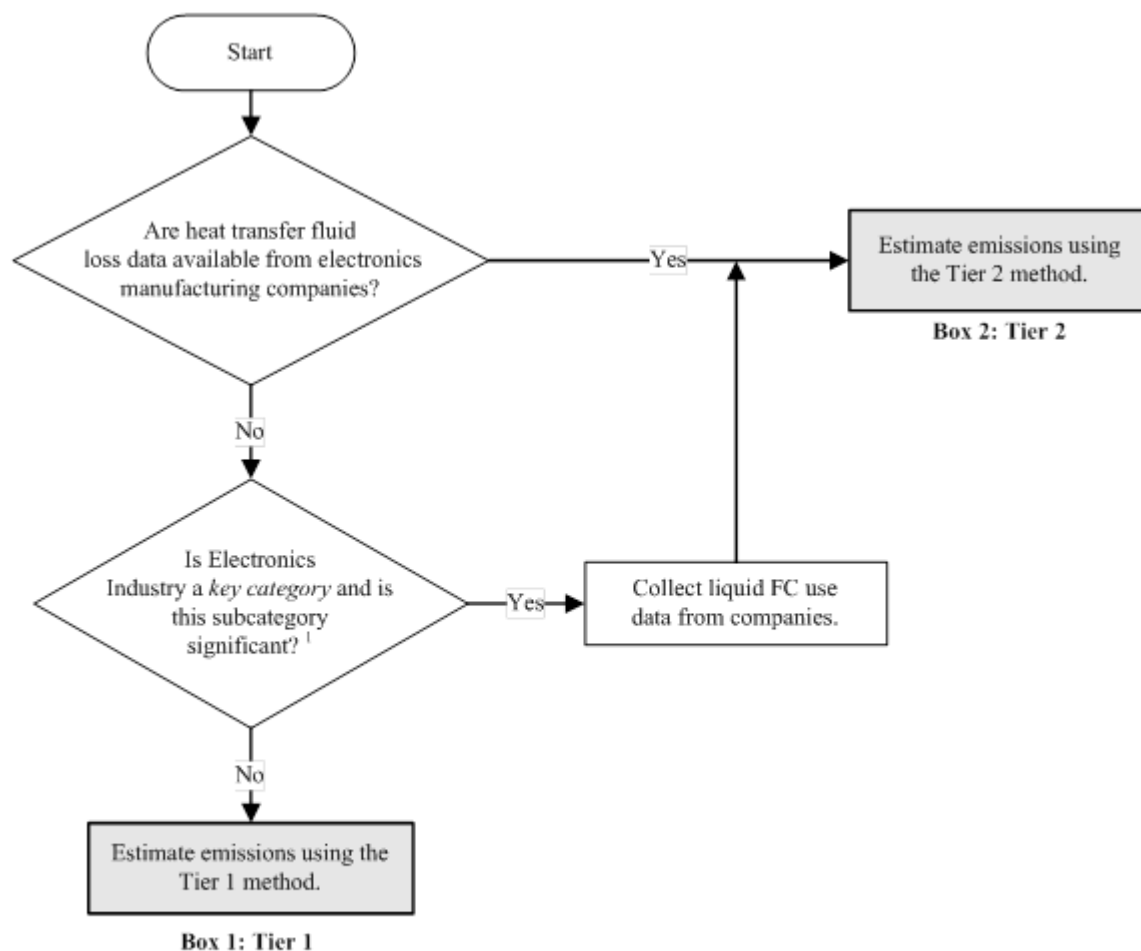
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1179 I_{it} = inventory of liquid FC_i in containers other than equipment at the end of the reporting year (in stock or
1180 storage), (litres).

1181 D_{it} = Disbursements of fluorinated heat transfer fluid i, including amounts returned to chemical suppliers,
1182 sold with or inside of equipment, and sent off-site for verifiable recycling or destruction (l).
1183 Disbursements should include only amounts that are properly stored and transported so as to prevent
1184 emissions in transit (litres).

1185

Figure 6.3 (unchanged) Decision tree for estimation of FC emissions from HT fluid loss from electronics manufacturing



Note:

1. See Volume 1 Chapter 4, Methodological Choice and Identification of Key Categories (noting Section 4.1.2 on limited resources), for discussion of *key categories* and use of decision trees

6.2.2 Choice of emission factors

In the case where a new input gas is used for which no default emission factor (1-U) has been established, facilities can estimate emissions using Tier 2 and assume a default emission factor (1-U) = 0.8 with by-product emission factors of 0.1 for both CF₄ and C₂F₆. Alternatively, facilities can undertake process emissions characterization under Tier 3a and measure (1-U) and BPE factors for those new processes without defaults while using Tier 2 defaults for existing processes.

6.2.2.1 ETCHING AND TFT CLEANING FOR SEMICONDUCTORS, LIQUID CRYSTAL DISPLAYS, AND PHOTOVOLTAICS

TIER 1

The default emission factors for the Tier 1 method are presented in Table 6.2 below.

In using Tier 1, it is not *good practice* to modify, in any way, the set of the gases (C) or the values of the emission factors assumed in Table 6.2. For any given electronics manufacturing facility, inventory compilers should not

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combine emissions estimated using the Tier 1 method with emissions estimated using the Tier 2 or 3 methods. For example, inventory compilers may not use the Tier 1 factor for CF₄ to estimate the emissions of CF₄ from semiconductors and combine it with the results of other gases from a Tier 2 or Tier 3 method. It should be also noted that the Tier 1 C emission factors presented in Table 6.2 should not be used for any purpose other than estimating annual process gas-aggregate emissions from semiconductor, display or PV manufacturing for compilation of the national greenhouse gas inventory. The semiconductor emissions are calculated based on the surface area of wafer produced. Display emissions are calculated based on the surface area of input glass in Array process. The emission factor of Display data comes from the World Display device Industry Cooperation Committee.

TABLE 6.2(UPDATED) TIER1 GAS-SPECIFIC EMISSION FACTORS FOR GASES EMISSIONS FROM ELECTRONICS MANUFACTURING ^A															
Electronics industry subsector	CF ₄	C ₂ F ₆	CHF ₃	CH ₂ F ₂	CH ₃ F	C ₂ H ₅ F	C ₃ F ₈	c-C ₄ F ₈	NF ₃	SF ₆	C ₄ F ₆	C ₅ F ₈	C ₄ F ₈ O	N ₂ O	C ₆ F ₁₄
Semiconductors, kg/m ²	0.90	1.00	0.04				0.05		0.04	0.20					
Display, g/input glass area m ²	0.75		0.0040						1.03	6.01			0.0011	2.55	
PV, g/m ²	5	0.2													
MEMS, g/m ²										1.02					
Heat transfer fluids, kg/m ²															0.3
^a These default emission factors are the best estimates by the authors of this chapter as of 1 July 2018. There is some room for further refinement in the future by further analysis of available underlying data.															

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TIER 2

TABLE 6.3(UPDATED)
TIER 2A METHOD – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING^{A, B}

Process Gas	CF ₄	C ₂ F ₆	CHF ₃	CH ₂ F ₂	CH ₃ F	C ₂ H ₅ F	C ₃ F ₈	C ₃ F ₈ Remote	c-C ₄ F ₈	NF ₃ Remote	NF ₃	SF ₆	C ₄ F ₆	C ₅ F ₈	COF ₂	F ₂	C ₄ F ₈ O	N ₂ O TFD	N ₂ O other
(1-U _i)	0.75	0.68	0.46	0.17	0.20	0.51	0.30	0.063	0.16	0.018	0.18	0.44	0.16	0.086	NA	NA	0.14	0.8	1.0
B _{CF4}	NA	0.20	0.09	0.064	0.061	NA	0.21	NA	0.078	0.045	0.043	0.085	0.095	0.11	NA	NA	0.13	NA	NA
B _{C2F6}	0.063	NA	0.047	0.039	0.016	0.0034	0.18	NA	0.034	NA	0.035	0.077	0.092	0.049	NA	NA	0.045	NA	NA
B _{C3F8}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.0001	NA	NA	NA	NA	NA
B _{C4F6}	NA	NA	0.0001	NA	NA	NA	NA	NA	0.018	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B _{C4F8}	0.00063	NA	0.0008	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B _{C5F8}	0.0012	NA	0.0012	NA	NA	NA	NA	NA	0.0086	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B _{CH3F}	0.0080	NA	0.0080	0.0080	NA	NA	0.0007	NA	NA	NA	NA	0.0080	NA	NA	NA	NA	NA	NA	NA
B _{CH2F2}	NA	NA	0.0036	NA	0.0023	NA	NA	NA	0.0015	NA	0.0009	0.00003	0.00003	NA	NA	NA	NA	NA	NA
B _{CHF3}	0.056	0.047	NA	0.050	0.0057	NA	0.012	NA	0.034	NA	0.025	0.0025	0.043	0.0054	NA	NA	NA	NA	NA

Source:

U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I). Emission factors are straight averages of the default emission factors in Tables I-11 and I-12, applicable to ≤200 and 300-mm fabs respectively. If one of the tables lacked an emission factor, the emission factor from the other table was used.

^a These default emission factors are the best estimates by the authors of this chapter as of 1 July 2018. There is some room for further refinement in the future by further analysis of available underlying data.

^b Similar default emission factors may be developed in the future also for display manufacturing, PV manufacturing, and MEMS manufacturing by analysis of available underlying data.

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TABLE 6.4 (NEW) TIER 2B METHOD – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING ^{A,B}																			
Process Gas	CF ₄	C ₂ F ₆	CHF ₃	CH ₂ F ₂	CH ₃ F	C ₂ H ₅ F	C ₃ F ₈	C ₃ F ₈ Remote	c-C ₄ F ₈	NF ₃ Remote	NF ₃	SF ₆	C ₄ F ₆	C ₅ F ₈	COF ₂	F ₂	C ₄ F ₈ O	N ₂ O TFD	N ₂ O other
≤200mm wafer size																			
(1-U _i)	0.85	0.56	0.50	0.13	0.064	0.51	0.40	NA	0.13	0.018	0.16	0.55	0.17	0.072	NA	NA	0.14		
B _{CF4}	NA	0.19	0.085	0.079	0.077	NA	0.20	NA	0.11	0.015	0.045	0.13	0.13	NA	NA	NA	0.13		
B _{C2F6}	0.046	NA	0.030	0.025	0.024	0.0034	NA	NA	0.037	NA	0.025	0.11	0.11	0.014	NA	NA	0.045		
B _{C3F8}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA		
B _{C5F8}	0.0012	NA	0.0012	NA	NA	NA	NA	NA	0.0086	NA	NA	NA	NA	NA	NA	NA	NA		
B _{CHF3}	0.10	0.047	NA	0.049	NA	NA	NA	NA	0.040	NA	NA	0.0012	0.066	0.0039	NA	NA	NA		
300mm wafer size																			
(1-U _i)	0.65	0.80	0.42	0.21	0.33	NA	0.20	0.063	0.18	0.018	0.20	0.32	0.15	0.10	NA	NA	NA		
B _{CF4}	NA	0.21	0.095	0.049	0.045	NA	0.21	NA	0.045	0.075	0.040	0.040	0.059	0.11	NA	NA	NA		
B _{C2F6}	0.079	NA	0.064	0.052	0.0087	NA	0.18	NA	0.031	NA	0.045	0.044	0.074	0.083	NA	NA	NA		
B _{C3F8}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.00012	NA	NA	NA		
B _{C4F6}	NA	NA	0.00010	NA	NA	NA	NA	NA	0.018	NA	NA	NA	NA	NA	NA	NA	NA		
B _{C4F8}	0.00063	NA	0.00080	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA		
B _{CH3F}	0.0080	NA	0.0080	0.0080	NA	NA	0.00073	NA	NA	NA	0.0080	NA	NA	NA	NA	NA	NA		
B _{CH2F2}	TBD	NA	0.0036	NA	0.0023	NA	NA	NA	0.0015	NA	0.00086	0.000029	0.000030	NA	NA	NA	NA		
B _{CHF3}	0.011	NA	NA	0.050	0.0057	NA	0.012	NA	0.027	NA	0.025	0.0037	0.019	0.0069	NA	NA	NA		
Source: U.S. EPA GHGRP, Subpart I. Emission factors are from Tables I-11 and I-12, applicable to ≤200 and 300-mm fabs respectively. With the exception of the emission factors for remote plasma cleaning, the emission factors in Tables I-11 and I-12 are averages of the factors calculated for each gas for etching and chamber cleaning, respectively, weighted by historical gas consumption in each process type by a representative set of U.S. fabs. ^a These default emission factors are the best estimates by the authors of this chapter as of 1 July 2018. There is some room for further refinement in the future by further analysis of available underlying data. ^b Similar default emission factors may be developed in the future also for display manufacturing, PV manufacturing, and MEMS manufacturing by analysis of available underlying data.																			

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TABLE 6.5 (NEW) TIER 2C METHOD (≤200MM) – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING ^{A,B}																	
Process Gas	CF ₄	C ₂ F ₆	CHF ₃	CH ₂ F ₂	CH ₃ F	C ₂ H ₅ F	C ₃ F ₈	C ₄ F ₈	NF ₃	SF ₆	C ₄ F ₆	C ₅ F ₈	COF ₂	F ₂	C ₄ F ₈ O	N ₂ O TFD	N ₂ O other
Etching or substrate cleaning																	
(1-U _i)	0.81	0.72	0.51	0.13	0.70	0.064	NA	0.14	0.19	0.55	0.17	0.0722	NA	NA	NA	NA	NA
B _{CF4}	NA	0.10	0.085	0.079	NA	0.077	NA	0.11	0.004	0.13	0.13	NA	NA	NA	NA	NA	NA
B _{C2F6}	0.046	NA	0.03	0.025	0.0034	0.024	NA	0.037	0.025	0.11	0.11	0.014	NA	NA	NA	NA	NA
B _{C5F8}	0.0012	NA	0.0012	NA	NA	NA	NA	0.0086	NA	NA	NA	NA	NA	NA	NA	NA	NA
B _{CH3F}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B _{CH2F2}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B _{CHF3}	0.10	0.047	NA	0.049	NA	NA	NA	0.04	NA	0.0012	0.066	0.0039	NA	NA	NA	NA	NA
Remote plasma cleaning																	
(1-U _i)	NA	NA	NA	NA	NA	NA	NA	NA	0.017	NA	NA	NA	NA	NA	NA	NA	NA
B _{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	0.015	NA	NA	NA	NA	NA	NA	NA	NA
In-situ plasma cleaning																	
(1-U _i)	0.92	0.55	NA	NA	NA	NA	0.40	0.10	0.18	NA	NA	NA	NA	NA	0.14	NA	NA
B _{CF4}	NA	0.21	NA	NA	NA	NA	0.20	0.11	0.05	NA	NA	NA	NA	NA	0.13	NA	NA
B _{C2F6}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.045	NA	NA
B _{C3F8}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
In-situ thermal cleaning																	
(1-U _i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B _{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
TFD																	
(1-U _i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.8	NA
Other																	
(1-U _i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0
Source: U.S. EPA GHGRP, Subpart I. Emission factors are from Table I-3.																	
^a These default emission factors are the best estimates by the authors of this chapter as of 1 July 2018. There is some room for further refinement in the future by further analysis of available underlying data.																	
^b Similar default emission factors may be developed in the future also for display manufacturing, PV manufacturing, and MEMS manufacturing by analysis of available underlying data.																	

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TABLE 6.6(NEW)
TIER 2C METHOD (300MM) – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING^{A,B}

Process Gas	CF ₄	C ₂ F ₆	CHF ₃	CH ₂ F ₂	CH ₃ F	C ₃ F ₈	C ₄ F ₈	NF ₃	SF ₆	C ₄ F ₆	C ₅ F ₈	COF ₂	F ₂	N ₂ O TFD	N ₂ O other
Etching or wafer cleaning															
(1-U _i)	0.65	0.80	0.42	0.21	0.33	0.30	0.18	0.15	0.32	0.15	0.10	NA	NA	NA	NA
B _{CF4}	NA	0.21	0.095	0.049	0.045	0.21	0.045	0.046	0.04	0.059	0.11	NA	NA	NA	NA
B _{C2F6}	0.079	NA	0.064	0.052	0.00087	0.18	0.031	0.045	0.044	0.074	0.083	NA	NA	NA	NA
B _{C3F8}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.00012	NA	NA	NA	NA
B _{C4F6}	NA	NA	0.0001	NA	NA	NA	0.018	NA	NA	NA	NA	NA	NA	NA	NA
B _{C4F8}	0.00063	NA	0.0008	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B _{CH3F}	0.008	NA	0.008	0.008	NA	0.00073	NA	0.008	NA	NA	NA	NA	NA	NA	NA
B _{CH2F2}	NA	NA	0.0036	NA	0.0023	NA	0.0015	0.00086	0.00003	0.00003	NA	NA	NA	NA	NA
B _{CHF3}	0.011	NA	NA	0.05	0.0057	0.012	0.027	0.025	0.0037	0.019	0.0069	NA	NA	NA	NA
Remote plasma cleaning															
(1-U _i)	NA	NA	NA	NA	NA	0.063	NA	0.017	NA	NA	NA	NA	NA	NA	NA
B _{CF4}	NA	NA	NA	NA	NA	NA	NA	0.075	NA	NA	NA	NA	NA	NA	NA
B _{CH3F}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B _{CH2F2}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B _{CHF3}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
In-situ plasma cleaning															
(1-U _i)	NA	NA	NA	NA	NA	NA	NA	0.23	NA	NA	NA	NA	NA	NA	NA
B _{CF4}	NA	NA	NA	NA	NA	NA	NA	0.037	NA	NA	NA	NA	NA	NA	NA
In-situ thermal cleaning															
(1-U _i)	NA	NA	NA	NA	NA	NA	NA	0.28	NA	NA	NA	NA	NA	NA	NA
B _{CF4}	NA	NA	NA	NA	NA	NA	NA	0.01	NA	NA	NA	NA	NA	NA	NA
TFD															
(1-U _i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.8	NA
Other															
(1-U _i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0

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Source: U.S. EPA GHGRP, Subpart I. Emission factors are from Table I-4.

^aThese default emission factors are the best estimates by the authors of this chapter as of 1 July 2018. There is some room for further refinement in the future by further analysis of available underlying data.

^bSimilar default emission factors may be developed in the future also for display manufacturing, PV manufacturing, and MEMS manufacturing by analysis of available underlying data.

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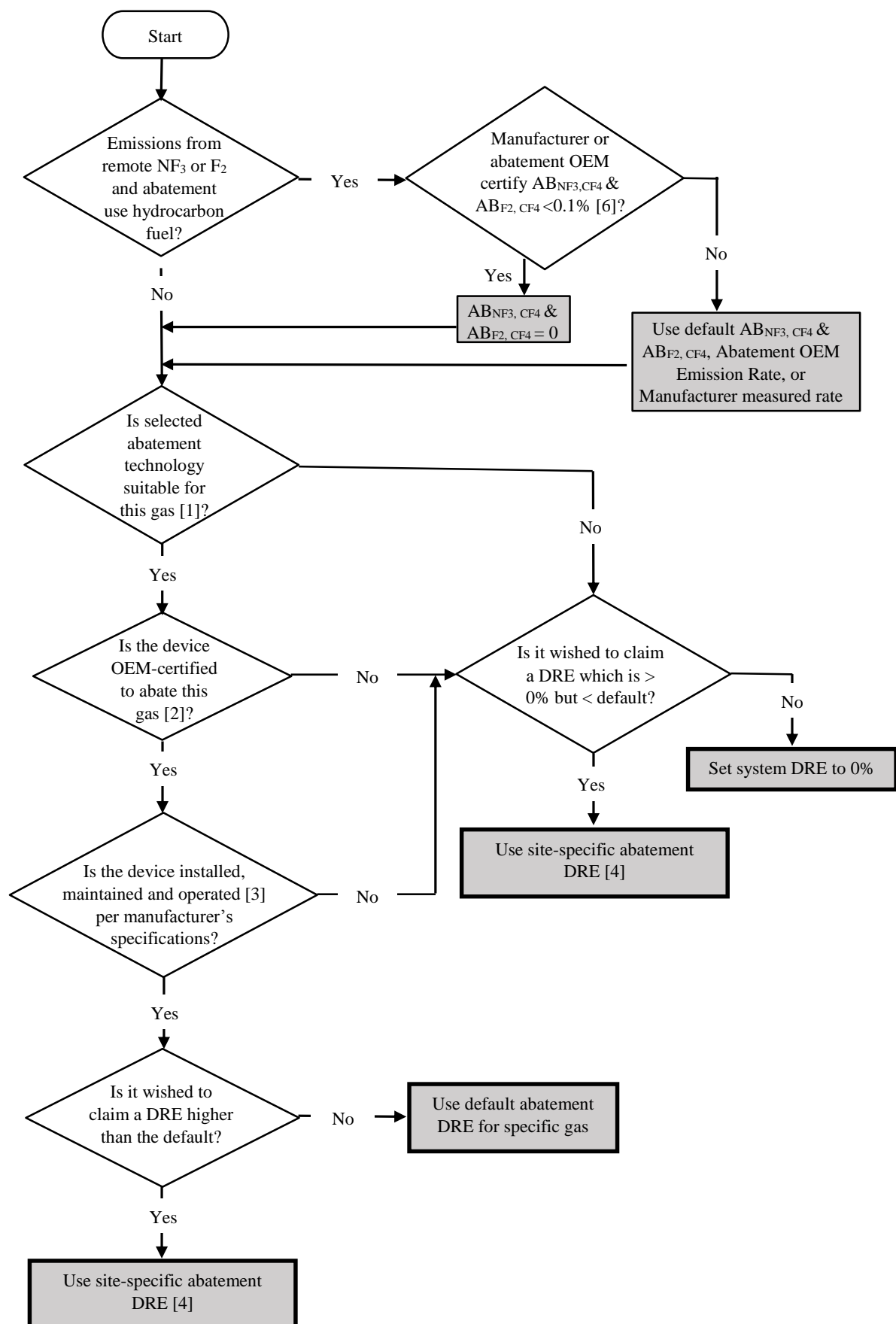
Emission control technology factors for Tier 2 methods

It is recognised that since the 2006 Guidelines, the varying performance of different abatement technologies needs to be accounted for (Table 6.7), both in terms of their emission reduction efficiencies ("Destruction Removal Efficiency", DRE) and their propensity to convert hydrocarbon fuel (such as methane or propane) into CF₄ by direct reaction with fluorine that is exhausted from TFD process tools during chamber cleaning that typically originate from NF₃.

Table 6.7 Abatement Suitability Table for Destruction Reaction Efficiency (DRE) of Process GHG Emissions (X=Suitable to use default DRE)

TABLE 6.7(NEW) ABATEMENT SUITABILITY TABLE																			
Abatement Technology	Process GHG Emission																		
	CF ₄	C ₂ F ₆	C ₄ F ₆	C ₄ F ₈	C ₄ F ₈ O ^a	C ₃ F ₈	CHF ₃	CH ₃ F ₂	C ₄ F ₆	C ₃ F ₈	C ₂ H ₆ F	C ₃ F ₆ O	C ₄ F ₆ O	CH ₃ F	C ₂ F ₄	COF ₂	NF ₃	SF ₆	N ₂ O
Cartridge (Media consumed)				X			X										X	X	
Catalyst (Media not consumed)	X																X	X	X
Hot-wet (electrical) < 800° C																			
Hot-wet (electrical) > 800° C			X	X												X	X		
Plasma	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Combustion	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
New technology	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
<p>Note:</p> <p>^a C₄F₈O is a new addition to table</p> <p>Abatement technology definitions:</p> <p>Cartridge – Any form of dry-bed passive gas treatment, either heated or ambient-temperature. The active media is consumed by reaction with the target gas.</p> <p>Catalyst – This includes wet or dry beds, possible heating of the catalyst bed, and possible wet pre- or post-scrubbing. The media is not consumed by reaction with the target gas, it simply reduces the energy barrier of the reaction chemistry.</p> <p>Hot-wet – This includes abatement described as “thermal wet” and indicates electrical heating followed by wet scrubbing. May also include a pre-wet scrubber.</p> <p>Plasma – This involves the use of plasmas (e.g. RF, dc or microwave) operated at atmospheric or sub-atmospheric pressures potentially combined with wet or dry scrubbing of by-products. May also include introduction of water, hydrogen and/or oxygen as chemical reagents.</p> <p>Combustion – This includes all configurations of fuel combustion and reaction zone configuration, water- or air-cooled, and dry or wet post-scrubbing.</p> <p>New Technology – This is to account for the possibility of new abatement technologies emerging that are not included in the categories above.</p> <p>“T” indicates that to be considered as being suitable for treating a specific gas, the OEM would need to provide testing data to that default DREs can be achieved using suitable EPA or ISMI methodologies that account for dilution and tested on representative gas flow conditions.</p>																			

1237 **Figure 6.4 (new) Decision Tree for Process GHG Emission Abatement Default Emission Factors**



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Note:

1. The abatement device is deemed suitable per the Applicability of process GHG emissions Abatement Technologies table. Note that this does not preclude new abatement technologies that have not been included in table 6.6A, but these need to be supported by OEM data to be included.
2. The fab defines its highest total FC flow through the abatement device (gas by gas) AND highest total flow scenario (with N2 dilution accounted for), abatement model (if there are more than one abatement models), and the fab requests the abatement manufacturer to certify that the default DRE can be met in the worst-case scenario (for each type of abatement system if more than one).
3. Proper operation requires all parameters to be within manufacturer's specifications, including items such as vacuum pump purge, fuel / oxidizer settings, supply and exhaust flows and pressures, and utilities to the abatement device (fuel gas flow and pressure, calorific value, water quality, flow & pressure, extract flow and pressure etc.).
4. The appropriate test method must be used (EPA, ISMI or similar accounting for dilution) and at a frequency of at least 5% of the installed abatement population annually for a representative sample of process applications.
5. With regards to abatement, "Exhaust gas" refers to the combination of all gases exiting the process chamber (unreacted precursors plus by-products formed in the process), plus any gases subsequently added such as pump purge gases.
6. ABNF3,CF4 = Fraction of NF3 in process exhaust gas that is converted into CF4 by direct reaction with hydrocarbon fuel and F2gas in a combustion abatement system. ABF2,CF4 = Fraction of F2 in process exhaust gas that is converted into CF4 by direct reaction with hydrocarbon fuel gas in a combustion abatement system. These are set to zero if the abatement OEM or electronics manufacturer can certify that the rate of conversion is <0.1%, otherwise use a default value, e.g. 0.093 kg CF4 per kg NF3 and 0.116 kg CF4 per kg F2. This is taken into account in calculations in Tier 2.

TABLE 6.8(NEW) TIER 2 DEFAULT DRE PARAMETERS FOR ELECTRONICS INDUSTRY PROCESS GHG EMISSION REDUCTION TECHNOLOGIES ^A												
Process Gas	CF ₄	CH ₃ F	CHF ₃	CH ₂ F ₂	C ₂ F ₆	C ₃ F ₈	C ₄ F ₆	c-C ₄ F ₈	C ₅ F ₈	SF ₆	NF ₃	N ₂ O
Tier 2a and 2b: Overall Default DREs												
	75%	60%	60%	60%	60%	60%	60%	60%	60%	60%	88%	60%
Tier 2c: Overall Default DREs												
Plasma Etch / Wafer Clean Process Type												
	75%	97%	97%	97%	97%	97%	97%	97%	97%	97%	96%	60%
Chamber Clean Process Type												
	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	88%	60%
Source: U.S. EPA GHGRP, Subpart I. Default DREs are from Table I-16. ^a These default emission factors are the best estimates by the authors of this chapter as of 1 July 2018. There is some room for further refinement in the future by further analysis of available underlying data.												

6.2.2.2 HEAT TRANSFER FLUIDS

TABLE 6.9 (NEW) TIER 1 DEFAULT EMISSION FACTORS FOR HEAT TRANSFER FLUIDS (HTFs), USING REPRESENTATIVE HTFs			
Representative HTF	Electronics Industry Sector		
	Semiconductor manufacturing (kg/m ²)	Semiconductor “burn-in” testing (kg/kpcs)	Display (kg/m ²)
HFE-449sl	0.06	1 x 10 ⁻⁴	0.00002
C ₆ F ₁₄	0.07	3 x 10 ⁻⁵	0.00004
PFPME	0.04	1 x 10 ⁻⁵	0.00004
Note: 1. The default emission factors for semiconductor manufacturing are based on the arithmetic average of the emission factors for the United States, Europe and Taiwan, Province of China. The US emission factors are based on reporting from several manufacturers in 2016. The European emission factors are based on reporting from four fabs, averaged over three years. The Taiwan emission factors are based on reporting from manufacturers representing 95% market share, averaged over five years. For all regions, the number of HTFs emitted was ten or more; these HTFs were sorted into three groups of chemically similar HTFs represented by the HTFs in the table. HFE-449sl is used to represent hydrofluoroethers; C ₆ F ₁₄ is used to represent fully fluorinated HTFs manufactured by 3M™; and PFPME is used to represent fully fluorinated HTFs manufactured by Solvay™. 2. The default emission factors for semiconductor “burn-in” testing are based on reporting by semiconductor manufacturers in Taiwan, Province of China, averaged over three and a half years. These manufacturers represent 80% of the market share in Taiwan. 3. The default emission factors for display are based on reporting by display manufacturers in Taiwan, Province of China, averaged over three years. These manufacturers represent 90% of market share in Taiwan. The number of HTFs emitted was seven; these HTFs were sorted into three groups of chemically similar HTFs represented by the HTFs in the table.			

6.2.3 Choice of activity data

Activity data for the electronics industry consists of data on gas sales/purchases and/or production figures (surface area of substrate used during the production of electronic devices, e.g. silicon, glass). For the more data-intensive Tier 2 methods, gas consumption data at the company or plant-level are necessary. For the Tier 1 methods, inventory compilers will need to determine the total surface area of electronic substrates used during the production of electronic devices for a given year. The best sources of either gas usage data or substrate area data are the owners and operators of the electronics manufacturing facilities in each country. However, if it is not possible to obtain the activity data from the owners and operators, Tier 1 estimates may be developed using data on substrate area that is available from purchasable databases. Silicon consumption may be estimated using an appropriate edition of the World Fab Watch (WFW) database, published quarterly by Semiconductor Equipment & Materials International (SEMI)⁴. The database contains a list of plants (production as well as R&D, pilot plants, etc.) worldwide, with information about location, design capacity, wafer size and much more. Similarly, SEMI’s ‘Flat Panel Display Fabs on Disk’ database provides an estimate of glass consumption for global TFT-Display manufacturing.

Table 6.7 of the 2006 IPCC Guidelines provides design capacity figures, but these values, which were estimated for 2003 through 2005, are no longer accurate. We are not updating Table 6.7 in this Refinement because the update would also lose its accuracy very quickly given the rapid pace of growth and change in the electronics industry. Nevertheless, the following guidance remains applicable to design capacity data extracted from the purchasable databases above. Semiconductor and TFT-Display manufacturing plants are not operated at design capacities for sustained periods, such as a full year. Instead, the production fluctuates depending on product demand. For semiconductor manufacturing, publicly available industry statistics show that the global annual average capacity utilisation during the period 1991 – 2000 varied between 76 and 91 percent, with an average value of 82 percent and most probable value of 80 percent (this section will be updated based on more recent figures). When country-specific capacity utilisation data are not available, the suggested capacity utilisation for semiconductor manufacturing is 80 percent (to be updated)]. This should be used consistently for a time series of estimates. For display manufacturing, publicly available capacity utilisation data are not available. The display

⁴ The term ‘fab’ is synonymous with clean room/manufacturing facility. Semiconductor and flat panel display manufacturing plants are often called fabrication plants, from which the abbreviation ‘fab’ follows.

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manufacturing industry, like the semiconductor manufacturing industry, lowers product prices to maintain the highest practical plant capacity utilisation. By analogy, therefore, it is suggested to use 80 percent to estimate substrate glass consumption using the design capacities provided in Table 6.7 for country TFT-Display manufacturers. For PV manufacturing, published capacity utilisation data ranges between 77 – 92 percent, with the average for the years 2003 and 2004 of 86 percent. Therefore, 86 percent is the recommended default figure for C_u (see Equation 6.1) to use (to be updated for PV and MEMS).

When estimating emissions during PV manufacture, one should account for the fraction of the industry that actually employs FCs (C_{PV} in Equation 6.1). Because recent surveys indicate that between 40 – 50 percent of PV manufacture actually uses process greenhouse gases, and the usage trend may be increasing, the recommended default value for C_{PV} is 0.5 (value to be updated).

6.2.4 Completeness

[This section may be refined in the final draft to ensure consistency with sections 6.2.1-6.2.3 above]

6.2.5 Developing a consistent time series

[This section may be refined in the final draft to ensure consistency with sections 6.2.1-6.2.3 above]

6.3 UNCERTAINTY ASSESSMENT

6.3.1 Emission factor uncertainties

[This section may be refined in the final draft to ensure consistency with sections 6.2.2 above]

6.3.2 Activity data uncertainty

[This section may be refined in the final draft to ensure consistency with sections 6.2.3 above]

6.4 QUALITY ASSURANCE / QUALITY CONTROL (QA/QC), REPORTING AND DOCUMENTATION

6.4.1 Quality Assurance / Quality Control (QA/QC)

[This section may be refined in the final draft to ensure consistency with sections 6.2-6.3 above]

6.4.2 Reporting and documentation

[This section may be refined in the final draft to ensure consistency with sections 6.2-6.3 above]

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