

# CHAPTER 6

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## ELECTRONICS INDUSTRY EMISSIONS

[Parts in yellow – comments from Authors/issues that will be refined further]

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

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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:

- A new Tier 2c method for semiconductors that accounts for the size of manufactured wafers in addition to the process type and input gas,
- A new Tier 3b method that relies on the measurement of emission factors at the stack level rather than the process level,
- 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,
- Updates to the methods and Tier 1 emission factor for fluorinated heat transfer fluids,
- Updates to the emission factors for Tier 1 and Tier 2 for all electronics industry types, and
- Corresponding updates to the Completeness; Time Series Consistency; Uncertainty; and QA/QC, Reporting and Documentation sections.]

### 6.1 INTRODUCTION

As part of its manufacturing processes, the electronics industry uses greenhouse gases (GHGs) such as fluorinated compounds (FCs) and nitrous oxide (N<sub>2</sub>O) 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 liquid crystal displays (LCDs) and organic light emitting devices (OLEDs).

The electronics industry currently emits both FCs that are gases at room temperature and FCs that are liquids at room temperature. The gases include perfluoromethane (CF<sub>4</sub>), perfluoroethane (C<sub>2</sub>F<sub>6</sub>), perfluoropropane (C<sub>3</sub>F<sub>8</sub>), perfluorocyclobutane (c-C<sub>4</sub>F<sub>8</sub>), 1,3-hexafluorobutadiene (C<sub>4</sub>F<sub>6</sub>), octafluorocyclopentene (c-C<sub>5</sub>F<sub>8</sub>), fluoromethane (CH<sub>3</sub>F), difluoromethane (CH<sub>2</sub>F<sub>2</sub>), trifluoromethane (CHF<sub>3</sub>), fluoroethane (C<sub>2</sub>H<sub>5</sub>F), nitrogen trifluoride (NF<sub>3</sub>), sulphur hexafluoride (SF<sub>6</sub>), carbonyl fluoride (COF<sub>2</sub>), and octafluorotetrahydrofuran (C<sub>4</sub>F<sub>8</sub>O). These gases are used in two important steps of electronics manufacturing: (i) plasma etching silicon containing materials and (ii) cleaning chemical vapour deposition (CVD) tool chamber-walls where silicon has deposited. 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-FPD 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 CVD chamber cleaning use high energies to break the FCs into fluorine atoms to perform these process steps. The majority of FC and N<sub>2</sub>O emissions results from the failure to completely break down the FCs (or N<sub>2</sub>O) 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 FC by-products such as CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub>, C<sub>4</sub>F<sub>6</sub>, C<sub>4</sub>F<sub>8</sub>, C<sub>3</sub>F<sub>8</sub>, CHF<sub>3</sub>, CH<sub>2</sub>F<sub>2</sub>, and CH<sub>3</sub>F. Also, formation of CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub>, CHF<sub>3</sub>, CH<sub>2</sub>F<sub>2</sub>, CH<sub>3</sub>F (and potentially other FCs) as by-products of etching or cleaning carbon-containing thin films must be taken into account, in particular for processes using molecular fluorine (F<sub>2</sub>), nitrogen trifluoride (NF<sub>3</sub>), sulphur hexafluoride (SF<sub>6</sub>), or chlorine trifluoride (ClF<sub>3</sub>) input gases.<sup>1</sup> [It should also be noted that CF<sub>4</sub> and N<sub>2</sub>O may be formed in abatement systems under certain conditions; the conditions for the formation of CF<sub>4</sub> and N<sub>2</sub>O in some abatement systems are still being investigated, and an adequate methodology for reporting such emissions (default emissions factor based on amount of input fuel/oxygen?) is still being devised]. With respect to liquid FCs, emissions occur through evaporative losses.

<sup>1</sup> When using cleaning or etching gases that do not contain carbon (e.g. F<sub>2</sub>, NF<sub>3</sub>, SF<sub>6</sub>, or ClF<sub>3</sub>), CF<sub>4</sub> and other FCs 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 CF<sub>4</sub> and other FC 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 F<sub>2</sub> or ClF<sub>3</sub>). Please see section 6.2.2.1 for more detail.

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These 2019 Refined Guidelines were designed to maintain the scientific validity of GHG emissions estimates from the electronics industry. Compared to the 2006 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 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 FC gases. As was the case in the 2006 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 CVD) is now replaced with a new Tier 2b method using emission factors applicable to different wafer sizes ( $\leq 200\text{mm}$  or  $\geq 300\text{mm}$  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 ( $\leq 200\text{mm}$  or  $\geq 300\text{mm}$  in the semiconductor sub-sector) and by refined process types (etch or substrate cleaning, remote plasma cleaning, in-situ plasma cleaning, thermal cleaning, CVD, and 'other'). Finally, compared to the 2006 Guidelines, [additional guidance is provided to apportion gas consumption to different process types]. [For the manufacturing of display, MEMS, and PV devices, additional information is being sought to determine whether applying some forms of the Tier 2b (distinguishing by substrate size) and Tier 2c are necessary and feasible for such sub-sectors].

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 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)[details of the Tier 3a method are still being devised]. Finally, the 2019 Refinement includes a new 'stack' Tier 3b method based on the measurement of site-specific emission factors at the stack level) [details of the Tier 3a method are still being devised].

## 6.2 METHODOLOGICAL ISSUES

### 6.2.1 Choice of Method

#### 6.2.1.1 ETCHING AND CVD CLEANING FOR SEMICONDUCTORS, LIQUID CRYSTAL DISPLAYS, AND PHOTOVOLTAICS

GHG emissions from the electronics industry vary according to the gases and processes used in manufacturing different types of electronic devices, the brand of process tools, 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 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) [Table 6.1 shall be updated to take into account the display, MEMS, and PV subsectors].

Continuous (in-situ) emissions monitoring is not currently considered an economically viable means to estimate emissions from the electronics industry. FC emissions are periodically measured, however, during the development of new processes and tools, generally for centreline process conditions.<sup>2</sup> 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 from measurements of centreline processes

<sup>2</sup> 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.

from a host of sources across industry, the higher tiered methods are based on measurements of site-specific centreline process conditions (Tier 3a), or on measurements of 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. pressure, temperature, plasma power, FC gas flow, processing time, 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 N<sub>2</sub>O, cleaning a CVD reactor after deposition of silicon nitride using NF<sub>3</sub>, etching of a trench in an interconnect structure using C<sub>4</sub>F<sub>6</sub>, etc.). In addition, the efficacy of FC emission control equipment depends on operating and maintaining the equipment according to the manufacturer’s specifications: increased gas flows, improper temperature settings, and failure to perform required maintenance will individually and collectively negatively impact performance.

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 utilization 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 lowered tiered ones, 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 allocating 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]. Thus, the use of higher tiered methods is strongly encouraged.

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 are 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 (allocate) 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, except that the NF<sub>3</sub> and C<sub>3</sub>F<sub>8</sub> emission factors are different for the remote clean technology and for ‘other’ (NF<sub>3</sub>- or C<sub>3</sub>F<sub>8</sub>-using) processes, and that the N<sub>2</sub>O emission factors are different for N<sub>2</sub>O CVD processes and for ‘other’ N<sub>2</sub>O-using processes (for all other gases there are no distinctions in the Tier 2a and Tier 2b methods between CVD 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 (allocate) gas consumption between CVD chamber cleaning technologies, etch, or substrate cleaning processes, or in cases where the gas consumption allocation 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 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) N<sub>2</sub>O CVD, and 6) N<sub>2</sub>O ‘other’. It should be noted that distinguishing emission factors by process type require allocation (apportionment) of gas consumption to each process type; for example, if NF<sub>3</sub> is used for both remote plasma cleaning, in-situ plasma cleaning, and etching, then the amount of NF<sub>3</sub> consumed for each of these three process types must be allocated. Such allocation may be based on actual measurements of gas consumption for each process type or on modelling {further guidance on modelling / apportioning gas consumption by process type to be developed}.

[Note: this paragraph will likely be moved to a box for the next version of the Refinement]. As discussed briefly in the introduction, the formation of CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub>, CHF<sub>3</sub>, CH<sub>2</sub>F<sub>2</sub>, CH<sub>3</sub>F (and potentially other FCs) as by-products of etching or cleaning carbon-containing thin films must be taken into account. To this effect, by-product emission



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factors ( $B_{CF_4,i}$ ,  $B_{C_2F_6,i}$ ,  $B_{CHF_3,i}$ ,  $B_{CH_2F_2,i}$ , and  $B_{CH_3F,i}$  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 does not contain carbon. This is because the fluorine atoms and other excited F species generated from the decomposition of  $NF_3$ ,  $SF_6$  or  $F_2$  can react with the carbon contained in the film to form  $CF_4$  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  $NF_3$ ,  $SF_6$ ,  $F_2$  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  $CF_4$  or other carbon-containing greenhouse gases are formed during the process. Thus, in such cases (and in such cases only), the  $NF_3$ ,  $SF_6$ , and  $F_2$  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, site-specific (measured) emission factors. In theory, the Tier 3a method could be used to assign an emission factor to each centreline process or each production recipe, 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 process-specific values, such as emission factors and gas consumption measured for each production recipe. Instead, it is possible to assign a single emission factor to multiple recipes, so long as the production recipes can be considered “similar” to the measured centreline processes [the definition of similarity is to be further developed as part of the refinement of the Tier 3a method]. 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 site-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. combustion, plasma, catalysis, dry-bed cartridge, etc.) 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.

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 estimates of emissions. For example, higher accuracy might be achieved by using the Tier 3a method for a specific gas and site-specific processes, and these estimates may be combined with estimates based on Tier 2c default emission factors for other gases and processes instead of using only the Tier 2c method. 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**  
**INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR ELECTRONICS MANUFACTURING**

[The information provided in this table is preliminary and likely to evolve as the definition of the various methods is refined]

Data		Tier 1	Tier 2			Tier 3	
			2a	2b	2c	3a	3b
Process Gas Entering Tools	$FC_{i_i}$ = consumption of gas $i$		Me/Mo	Me/Mo			
	$FC_{i,p}$ = consumption of gas $i$ for process $p$ . <sup>a</sup>				Me/Mo <sup>a</sup>	Me/Mo <sup>a</sup>	
	$C_{i,i}$ = kg of gas $i$ fed into tools connected to stack $j$ .						Me/Mo
	$h_i$ = 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 <sup>a</sup>	Me <sup>a</sup>	
	$U_{i,j}$ = 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 <sup>a</sup>	Me <sup>a</sup>	
	$B_{ijk}$ = 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 $j$						Me
Downstream FC Emission Control	$a_i$ = Fraction of gas $i$ volume used in processes with certified FC emission control technology		Me	Me			
	$a_{i,p}$ = Fraction of gas $i$ volume fed into processes $p$ with certified FC emission control technology				Me <sup>a</sup>	Me <sup>a</sup>	
	$a_{ij}$ = 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 <sup>a</sup>	D/Me <sup>a</sup>	
	$D_{j,i}$ = Fraction of input gas $i$ destroyed or removed in abatement systems connected to process tools that are vented to stack system $j$						Me
	$D_{j,k}$ = 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 <sup>a</sup>	Me <sup>a</sup>	
	$UT_j$ = 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
Annual Production Capacity	$P$ = Annual production in surface area of substrate produced	Me					
	$C_{PV}$ = fraction of PV manufacture that uses FCs (PV subsector only)	Mo					

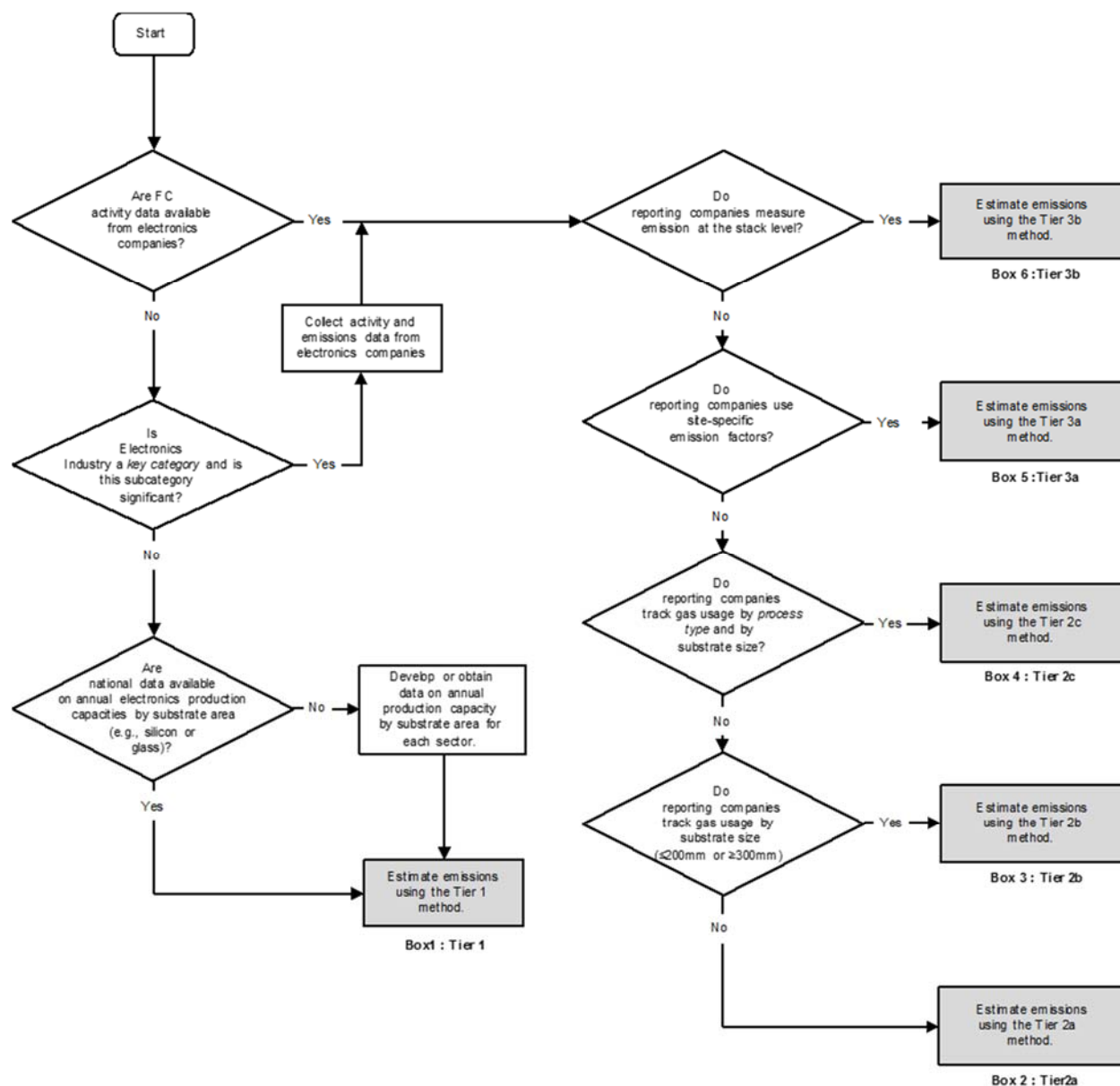
Me = measurement; Mo = model {modelling criteria TBD}; D = Use default factors from guidance.

<sup>a</sup> 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 Decision tree for estimation of GHG emissions from electronics manufacturing**

[The authors still need to determine the extent to which all tiered methods can apply to sub-sectors other than semiconductor (i.e. display, PV, MEMS), and whether the decision tree of Figure 6.1 needs to be adapted to reflect the specificities of such sub-sectors]



## 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 FC and N<sub>2</sub>O 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, the default emission factors are multiplied by the annual production (P, in units of giga square meters (Gm<sup>2</sup>)). 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 FCs varies widely during PV manufacture, a third factor to account for the proportion of PV manufacture that employs FC is needed to estimate FC emissions from PV cells manufacturing. The Tier 1 formula is shown in Equation 6.1.

## EQUATION 6.1

## TIER 1 METHOD FOR ESTIMATION OF THE SET OF FC EMISSIONS

$$\{FC_i\}_n = \{EF_i \bullet P \bullet [C_{PV} \bullet \delta + (1 - \delta)]\}_n \quad (i = 1, \dots, n)$$

Where:

$\{FC_i\}_n$  = emissions of FC gas  $i$ , 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.

$EF_i$  = FC 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  $i$ )/m<sup>2</sup>.

$P$  = annual production, Gm<sup>2</sup> 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.

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

$\delta$  = 1 when Equation 6.1 is applied to PV industry and zero when Equation 6.1 is applied to either semiconductor or TFT-FPD 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 CF<sub>4</sub> to estimate the emissions of CF<sub>4</sub> 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.)

## TIER 2A METHOD

The Tier 2a method is based on default emission factors that represent average utilization efficiencies of the gases used in manufacturing processes ( $U_i$ ) and the formation of by-products during the used of each input gas ' $i$ ' ( $B_{CF4,i}$ ,  $B_{C2F6,i}$ ,  $B_{C3F8,i}$ ,  $B_{C4F6,i}$ ,  $B_{C4F8,i}$ ,  $B_{C5F8,i}$ ,  $B_{CHF3,i}$ ,  $B_{CH2F2,i}$ , or  $B_{CHF3,i}$ ). Please see [Tables 6.3A, 6.3B, 6.3C, and 6.3D] for the Tier 2a default emission factors for semiconductor, display, PV, and MEMS subsectors respectively. 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), 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  $N_2O$  CVD processes vs. 'other'  $N_2O$ -using processes. Thus, when using the Tier 2a method, the consumption of  $C_3F_8$ ,  $NF_3$ , and  $N_2O$  should be allocated between their different uses, as applicable to each reporting site. [Please see the guidance for allocating gas usage for further detail]. [Additional details to be added as applicable to other sub-sectors, i.e. display, MEMS, PV].

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  $i$  ( $FC_i$ ) 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 values {a method for developing site-specific  $h_i$  values will be added as part of a side box}. 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 6.2A, and 6.3A below.

### EQUATION 6.2A

#### EMISSIONS OF $FC_i$

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

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.

$FC_i$  = consumption of input gas  $i$  ( $i = CF_4$ ,  $C_2F_6$ ,  $C_3F_8$ ,  $C_4F_6$ ,  $c\text{-}C_4F_8$ ,  $C_5F_8$ ,  $c\text{-}C_4F_8O$ ,  $CHF_3$ ,  $CH_2F_2$ ,  $CH_3F$ ,  $C_2H_5F$ ,  $COF_2$ ,  $F_2$ ,  $N_2O$ ,  $NF_3$ ,  $SF_6$ ), 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 6.4.

### EQUATION 6.3A

#### BY-PRODUCT EMISSIONS

$$BPE_k = \sum_i (1 - h_i) \cdot B_{k,i} \cdot FC_i \cdot (1 - D_k)$$

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.

$FC_i$  = consumption of input gas  $i$

$B_{k,i}$  = 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 6.3B (replacing  $i$  by  $k$  indexes).

### EQUATION 6.3B

#### 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 6.3C]

$d_i$  = Destruction Removal Efficiency (DRE) for gas  $i$ , fraction.

$UT$  = average uptime of all abatement systems, fraction, calculated per Equation 6.3D.

### EQUATION 6.3C

#### ESTIMATE OF THE FRACTION OF GAS I VOLUME IN PROCESSES WITH EMISSION CONTROL TECHNOLOGIES

$$a_i = \frac{(n_a + \gamma \cdot m_a)}{(n + \gamma \cdot m)}$$

[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 CVD tools equipped with suitable abatement technology (site-specific).

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

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

$\gamma$  = factor reflecting the ratio of the uncontrolled emissions of gas  $i$  from CVD tools to the uncontrolled emissions of gas  $i$  from etch and wafer cleaning tools. {a default  $\gamma$  factor will be determined as part of the SOD and guidance will be provided for facilities wishing to estimate their own  $\gamma$  factor when the default factor will not be deemed suitable.]

### EQUATION 6.3D

#### 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

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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  $B_{BP,i}$  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 ( $h_i, FC_i, D_i, a_i, d_i, UT, Td_n$ , 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 ( $E_i$ ) plus the emissions of by-products ( $BPE_{CF_4,i}, BPE_{C_2F_6,i}, BPE_{CHF_3,i}, BPE_{C_3F_8,i}, BPE_{C_4F_6,i}, BPE_{C_4F_8,i}, BPE_{C_5F_8,i}, BPE_{CH_3F,i}$ , and  $BPE_{CH_2F_2,i}$ ) resulting from the conversion of all gases  $i$  used during production, as calculated using Equations 6.2, to 6.14. [Note: Tables 6.8, 6.9, 6.10 have been put as placeholders to include Tier 2b method default factors for the display, MEMS, and PV subsectors if the Tier 2b method are deemed applicable to these sub-sectors (analysis ongoing)].

**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)  $N_2O$  CVD, and 6)  $N_2O$  'other'. Please see {Tables 6.11 to 6.15} for the default Tier 2c emission factors {Tables 6.11 and 6.12 will include default Tier 2c emission factors for the semiconductor sub-sector ( $\leq 200\text{mm}$  and  $\geq 300\text{mm}$  wafer sizes respectively). Tables 6.13, 6.14, 6.15 have been put as placeholders to include Tier 2c method default factors for the display, MEMS, and PV subsectors if the Tier 2c method are deemed applicable to these sub-sectors (analysis ongoing)}. 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 allocating gas consumption by process type, which introduces additional complexity. [Please see the guidance for allocating 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 6.7A and 6.8A as shown below:

**EQUATION 6.7A****EMISSION OF  $FC_i$** 

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

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.

$FC_{i,p}$  = consumption of input gas  $i$  ( $i = CF_4, C_2F_6, C_3F_8, C_4F_6, C_4F_8, C_5F_8, C_4F_8O, CHF_3, CH_2F_2, CH_3F, C_2H_5F, COF_2, F_2, N_2O, NF_3, SF_6$ ), 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 6.8B.

$p$  = process type.

**EQUATION 6.8A**  
**BY-PRODUCT EMISSIONS**

$$BPE_k = \sum_i [(1 - h_i) \cdot \sum_p [B_{k,i,p} \cdot FC_{i,p} \cdot (1 - D_{k,p})]]$$

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  $p$ .

$D_{k,p}$  = overall reduction of gas  $k$  by-product emissions for process type  $p$ , fraction, calculated per Equation 6.8B (replacing  $i$  by  $k$  indexes).

$p$  = process type.

**EQUATION 6.8B**  
**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  $\gamma$  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 6.8C.

**EQUATION 6.8C**  
**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



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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.

## TIER 3 METHODS – SITE-SPECIFIC PARAMETERS

### TIER 3A METHOD [WORK IN PROGRESS]

[The Tier 3a method uses the same set of equations as the Tier 2c method. However, the Tier 3a method can use site-specific values for the parameters used in equations 6.7 to 6.10. Notably, ‘p’ in these equations can represent a site-specific ‘process’, having a more refined definition than the six ‘process types’ defined in the Tier 2c method. In the Tier 3a method, a process ‘p’ can be defined as a centreline process for which site-specific emission factors can be used. However, using the Tier 3a method does not require knowledge of the emission factors for each recipe run in the facility; instead, it is possible to assign a single emission factor to multiple recipes, so long as the production recipes can be considered ‘similar’ to the measured centreline processes {the definition of similarity is to be further developed as part of the refinement of the Tier 3a method.}]

### TIER 3B METHOD [WORK IN PROGRESS]

[Stack testing measures the amount of regulated pollutants or surrogates emitted from a specific facility<sup>3</sup>. It is a method commonly used by semiconductor fabs to quantify emissions and demonstrate compliance with State and Federal air permits 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. Although the individual plasma etch and chamber clean operations that use process greenhouse gases 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 an inability to track gas use during testing or abatement uptime during testing.

#### Preliminary Estimate of Emissions to Determine Which Stacks Must be Tested

Identify fab stacks that exhaust GHG emissions above threshold quantities by calculating preliminary emissions estimate for each stack using Tier 2b default EF and BF]

#### [EQUATION 6.8D]

##### PRELIMINARY ESTIMATE OF STACK PROCESS GAS EMISSIONS

$$E_{ij} = C_{ij} * (1 - U_{ij}) * (1 - (a_{ij} * D_{ij} * UT_j)) * 0.001 \text{ [need to change subscripts]}$$

[Where:

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

$C_{ij}$  = 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).

1. U.S. EPA, *Clean Air Act National Stack Testing Guidance*, April 27, 2009, <http://www.epa.gov/compliance/resources/policies/monitoring/caa/stacktesting.pdf>.

$a_{ij}$  = Ratio of the number of tools using input gas  $i$  that have abatement systems that are vented to stack system  $j$ , (expressed as a decimal fraction).

$D_{ij}$  = 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).

$UT_{ij}$  = The average uptime factor of all abatement systems connected to process tools vented to stack  $j$ , as calculated in Equation \_\_\_\_\_, on a stack basis (expressed as a decimal fraction).

0.001 = Conversion factor from kg to metric tons.

$i$  = Input gas.

$j$  = Stack system]

**[EQUATION 6.8E]**

**PRELIMINARY ESTIMATE OF BY-PRODUCT EMISSIONS FROM STACK**

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

[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).

$a_{ij}$  = Fraction of input gas  $i$  used for process sub-type, or process type  $j$  with abatement systems, on a fab basis (expressed as a decimal fraction).

$D_{jk}$  = 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 emitting by-product gas  $k$ , formed from input gas  $i$  connected to tools vented to stack  $j$  (expressed as a decimal fraction). For this equation,  $UT_{ijk}$  is assumed to be equal to  $UT_{ij}$  as calculated in Equation \_\_\_\_\_ on a stack basis.

0.001 = Conversion factor from kg to metric tons.

$i$  = Input gas.

$j$  = Stack system.

$k$  = By-product gas.]

[Rank the F-GHG emitting stack systems at the fab from lowest to highest emitting and determine stacks that must be tested.

- Tested stacks must represent a minimum of 85% of total fab CO<sub>2</sub>e emissions;
- The sum of the F-GHG emissions from all combined stack systems in the fab that are not tested must be less than 10,000 metric tons CO<sub>2</sub>e per year.

Testing Frequency [additional work must be completed to determine testing frequency]

- Multiple tests in first year?
- Fabs which use the stack test option will test major F-gas emitting stacks annually for X consecutive years.
- ✓ Acceptable level of variation, update EFs and BEFs with new data.
- Thereafter, testing in the subsequent year is required whenever:

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✓ The weight % makeup of an individual F-gas changes by more than 10 percentage points from one year to the next year, or

✓ If the fraction of abated tools decreases by greater than 10 %.

- If no significant changes occur, the EF determined from the initial X years of testing may be used for 5 years.

- After X consecutive years of testing, at a minimum, stacks would be re-tested every 5 years.

**Stack test method:**

- 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.

- Sample each stack for a minimum period of 8 hours.

- Stacks may be sampled sequentially or concurrently.

- Document test results using GD-043 or equivalent.

- Measure fab gas usage during a time period that encompasses stack testing.

- For each gas determine emission factor (EF) by summing emissions from all stacks and dividing by total gas used by the fab during testing. [Add equation]

- Adjust EF for gases that fall below detection limits. [details to be determined]

- Adjust EF for gases not used in process, but formed as by-products and detected.

- Determine annual usage of each gas from inventory or purchase records.

- Calculate annual emissions for each GHG by multiplying EF by annual gas usage. [Add equation]

- Track abatement units downtime and adjust annual emissions of each gas accordingly. [evaluate allowing fabs that do not interlock abatement with process equipment to develop default uptime using fab internal records].

- Report annual emissions.

Other considerations: Simplify emissions calculations so that apportioning of gas use is minimized. Conduct error analysis in coming months to determine how to handle untested stacks].

**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).

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 FC 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. It is the less accurate of the two methods for estimating emissions from losses of heat transfer fluids. The method, unlike the Tier 2 method,

gives an estimate of aggregate emissions—a weighted average emissions across all liquid FCs. The calculation relies on a generic emissions factor that expresses the average aggregate emissions per unit of silicon consumed during electronic devices manufacturing. 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 6.12A. In this instance the assumed FC is C<sub>6</sub>F<sub>14</sub>.

**EQUATION 6.12A****TIER 1 METHOD FOR ESTIMATION OF TOTAL FC EMISSIONS FROM HEAT TRANSFER FLUIDS**

$$FC_{\text{liquid, total}} = E_1 * P$$

Where:

$FC_{\text{liquid, total}}$  = Total FC emissions (Mt-CO<sub>2</sub>)

$E_1$  = aggregate emissions per Gm<sup>2</sup> of silicon consumed during the period, (Mt-CO<sub>2</sub>/Gm<sup>2</sup>)

$P$  = annual production, Gm<sup>2</sup> 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 Tier 2 method neglects fluid losses during filling new or existing equipment or when decommissioning old equipment (which is reasonable for these costly fluids).<sup>4</sup> The company should provide the chemical composition of the fluid(s) for which emissions are estimated.<sup>5</sup> The method is expressed in Equation 6.13.

**EQUATION 6.13****TIER 2 METHOD FOR ESTIMATION OF FC EMISSIONS FROM HEAT TRANSFER FLUIDS**

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

Where:

$\rho_i$  = density of liquid FC<sub>*i*</sub> (kg/litre)

$i$  = Fluorinated heat transfer fluid

$I_{it-1}(l)$  = the inventory of liquid FC<sub>*i*</sub> (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 must be the same as the inventory at the end of the previous year

$P_{it}(l)$  = Acquisitions of liquid FC<sub>*i*</sub> 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

$N_{it}(l)$  = 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)

$R_{it}(l)$  = 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)

<sup>4</sup> Prices for heat transfer fluids vary from \$55 – 130/litre {Prices to be updated}. 3M, a manufacturer of a popular heat transfer fluid estimates that a vintage 2000 manufacturing plant may lose 1900 litres/year via evaporation. Manufacturers of testing equipment that use heat transfer fluids report loss rates of approximately 30 litres/year/system for newer designs that reduce evaporative losses and 50 litres/year/system for older designs.

<sup>5</sup> In the absence of GWP estimates, the appropriate GWP for C<sub>6</sub>F<sub>14</sub> 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.

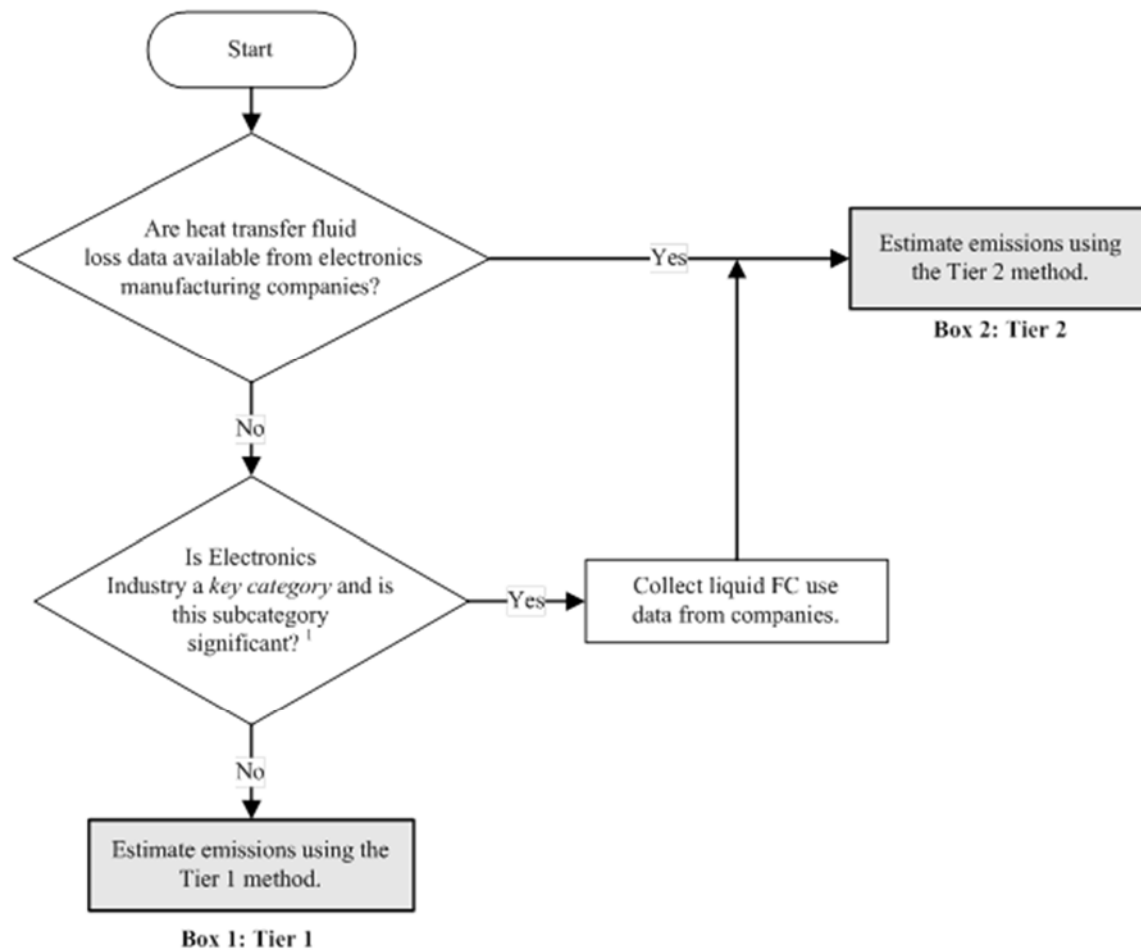
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686  $I_{it}(l)$  = inventory of liquid  $FC_i$  in containers other than equipment at the end of the reporting year (in stock  
687 or storage), (litres)

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

692

**Figure 6.2 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

[Note for the reviewers: in the following pages, a preview of the tables of default emission factors is provided for each Tier 2 method under consideration at the time of submission of this FOD. In the tables, the cells highlighted in grey are those for which there are existing EFs (in either the 2006 IPCC Guidelines or the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP) Subpart I tables + 2017 SIA data); the cell highlighted in yellow are those for which there are no existing EFs, but where some factors can be expected as part of the 2019 Refinement. These tables are subject to change as additional data is currently being collected].

### 6.2.2.1 ETCHING AND CVD 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 FCs or the values of the emission factors assumed in Table 6.2. For any given electronics manufacturing facility, inventory compilers should not 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 CF<sub>4</sub> to estimate the emissions of CF<sub>4</sub> from semiconductors and combine it with the results of other FC gases from a Tier 2 or Tier 3 method. It should be also noted that the Tier 1 FC emission factors presented in Table 6.2 should not be used for any purpose other than estimating annual FC-aggregate emissions from semiconductor, TFT-FPD or PV manufacturing for compilation of the national greenhouse gas inventory.

TABLE 6.2 TIER1 GAS-SPECIFIC EMISSION FACTORS FOR FC EMISSIONS FROM ELECTRONICS MANUFACTURING															
Electronics industry subsector	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	C <sub>2</sub> H <sub>5</sub> F	C <sub>3</sub> F <sub>8</sub>	c-C <sub>4</sub> F <sub>8</sub>	NF <sub>3</sub>	SF <sub>6</sub>	C <sub>4</sub> F <sub>6</sub>	C <sub>3</sub> F <sub>8</sub>	C <sub>4</sub> F <sub>8</sub> O	N <sub>2</sub> O	C <sub>6</sub> F <sub>14</sub>
Semiconductors, kg/m <sup>2</sup>															
Display, g/m <sup>2</sup>															
PV, g/m <sup>2</sup>															
MEMS, g/m <sup>2</sup>															
Heat transfer fluids, kg/m <sup>2</sup>															

## TIER 2

### Tier 2a Method

TABLE 6.3 TIER 2A METHOD – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING																			
Process Gas	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	C <sub>2</sub> H <sub>5</sub> F	C <sub>3</sub> F <sub>8</sub>	C <sub>3</sub> F <sub>8</sub> Remote	c-C <sub>4</sub> F <sub>8</sub>	NF <sub>3</sub> Remote	NF <sub>3</sub>	SF <sub>6</sub>	C <sub>4</sub> F <sub>6</sub>	C <sub>5</sub> F <sub>8</sub>	COF <sub>2</sub>	F <sub>2</sub>	C <sub>4</sub> F <sub>8</sub> O	N <sub>2</sub> O CVD	N <sub>2</sub> O other
(1-U <sub>i</sub> )																			
B <sub>CF4</sub>																			
B <sub>C2F6</sub>																			
B <sub>C3F8</sub>																			
B <sub>C4F6</sub>																			
B <sub>C4F8</sub>																			
B <sub>C5F8</sub>																			
B <sub>CH3F</sub>																			
B <sub>CH2F2</sub>																			

[Table 6.3A (placeholder) - Tier 2a method – Default emission factors for GHG emissions from display manufacturing]

[Table 6.3B (placeholder) - Tier 2a method – Default emission factors for GHG emissions from PV manufacturing]

[Table 6.3C (placeholder) - Tier 2a method – Default emission factors for GHG emissions from MEMS manufacturing]

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[Tier 2b Method]

TABLE 6.3D TIER 2B METHOD – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING																			
Process Gas	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	C <sub>2</sub> H <sub>5</sub> F	C <sub>3</sub> F <sub>8</sub>	C <sub>3</sub> F <sub>8</sub> Remote	c-C <sub>4</sub> F <sub>8</sub>	NF <sub>3</sub> Remote	NF <sub>3</sub>	SF <sub>6</sub>	C <sub>4</sub> F <sub>6</sub>	C <sub>5</sub> F <sub>8</sub>	COF <sub>2</sub>	F <sub>2</sub>	C <sub>4</sub> F <sub>8</sub> O	N <sub>2</sub> O CVD	N <sub>2</sub> O other
≤200mm wafer size																			
(1-U <sub>i</sub> )																			
B <sub>CF4</sub>																			
B <sub>C2F6</sub>																			
B <sub>C3F8</sub>																			
B <sub>C5F8</sub>																			
B <sub>CH3F</sub>																			
≥300mm wafer size																			
(1-U <sub>i</sub> )																			
B <sub>CF4</sub>																			
B <sub>C2F6</sub>																			
B <sub>C3F8</sub>																			
B <sub>C4F6</sub>																			
B <sub>C4F8</sub>																			
B <sub>CH3F</sub>																			
B <sub>CH2F2</sub>																			
B <sub>CHF3</sub>																			

[Table 6.3E (placeholder in case Tier 2b method for display manufacturing is feasible) - Tier 2B method – Default emission factors for GHG emissions from display manufacturing]

[Table 6.3F (placeholder in case Tier 2b method for PV manufacturing is feasible) - Tier 2B method – Default emission factors for GHG emissions from PV manufacturing]

[Table 6.3G (placeholder in case Tier 2b method for MEMS manufacturing is feasible) - Tier 2B method – Default emission factors for GHG emissions from MEMS manufacturing]

[Tier 2c Method ( $\leq 200\text{mm}$ )]

TABLE 6.3H TIER 2C METHOD (≤200MM) – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING																	
Process Gas	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	C <sub>2</sub> H <sub>5</sub> F	C <sub>3</sub> F <sub>8</sub>	c-C <sub>4</sub> F <sub>8</sub>	NF <sub>3</sub>	SF <sub>6</sub>	C <sub>4</sub> F <sub>6</sub>	C <sub>5</sub> F <sub>8</sub>	COF <sub>2</sub>	F <sub>2</sub>	C <sub>4</sub> F <sub>8</sub> O	N <sub>2</sub> O CVD	N <sub>2</sub> O other
Etching or substrate cleaning																	
(1-U <sub>i</sub> )																	
B <sub>CF4</sub>																	
B <sub>C2F6</sub>																	
B <sub>C5F8</sub>																	
B <sub>CH3F</sub>																	
B <sub>CH2F2</sub>																	
B <sub>CHF3</sub>																	
Remote plasma cleaning																	
(1-U <sub>i</sub> )																	
B <sub>CF4</sub>																	
In-situ plasma cleaning																	
(1-U <sub>i</sub> )																	
B <sub>CF4</sub>																	
B <sub>C2F6</sub>																	
B <sub>C3F8</sub>																	
In-situ thermal cleaning																	
(1-U <sub>i</sub> )																	
B <sub>CF4</sub>																	
CVD																	
(1-U <sub>i</sub> )																	
Other																	
(1-U <sub>i</sub> )																	

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[Tier 2c Method ( $\geq 300\text{mm}$ )]

<b>TABLE 6.3I</b> <b>TIER 2C METHOD (<math>\geq 300\text{MM}</math>) – DEFAULT EMISSION FACTORS FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING</b>															
Process Gas	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	CH <sub>3</sub> F	C <sub>3</sub> F <sub>8</sub>	c-C <sub>4</sub> F <sub>8</sub>	NF <sub>3</sub>	SF <sub>6</sub>	C <sub>4</sub> F <sub>6</sub>	C <sub>5</sub> F <sub>8</sub>	COF <sub>2</sub>	F <sub>2</sub>	N <sub>2</sub> O CVD	N <sub>2</sub> O other
<b>Etching or wafer cleaning</b>															
(1-U <sub>i</sub> )															
BCF <sub>4</sub>															
BC <sub>2</sub> F <sub>6</sub>															
BC <sub>3</sub> F <sub>8</sub>															
BC <sub>4</sub> F <sub>6</sub>															
BC <sub>4</sub> F <sub>8</sub>															
BCH <sub>3</sub> F															
BCH <sub>2</sub> F <sub>2</sub>															
BCHF <sub>3</sub>															
<b>Remote plasma cleaning</b>															
(1-U <sub>i</sub> )															
BCF <sub>4</sub>															
BCH <sub>3</sub> F															
BCH <sub>2</sub> F <sub>2</sub>															
BCHF <sub>3</sub>															
<b>In-situ plasma cleaning</b>															
(1-U <sub>i</sub> )															
BCF <sub>4</sub>															
<b>In-situ thermal cleaning</b>															
(1-U <sub>i</sub> )															
BCF <sub>4</sub>															
<b>CVD</b>															
(1-U <sub>i</sub> )															
<b>Other</b>															
(1-U <sub>i</sub> )															

[Table 6.3J (placeholder in case Tier 2c method for display manufacturing is feasible) - Tier 2c method – Default emission factors for GHG emissions from display manufacturing]

[Table 6.3K (placeholder in case Tier 2c method for PV manufacturing is feasible) - Tier 2c method – Default emission factors for GHG emissions from PV manufacturing]

[Table 6.3L (placeholder in case Tier 2c method for MEMS manufacturing is feasible) - Tier 2c method – Default emission factors for GHG emissions from MEMS manufacturing]

**Emission control technology factors for Tier 2 methods**

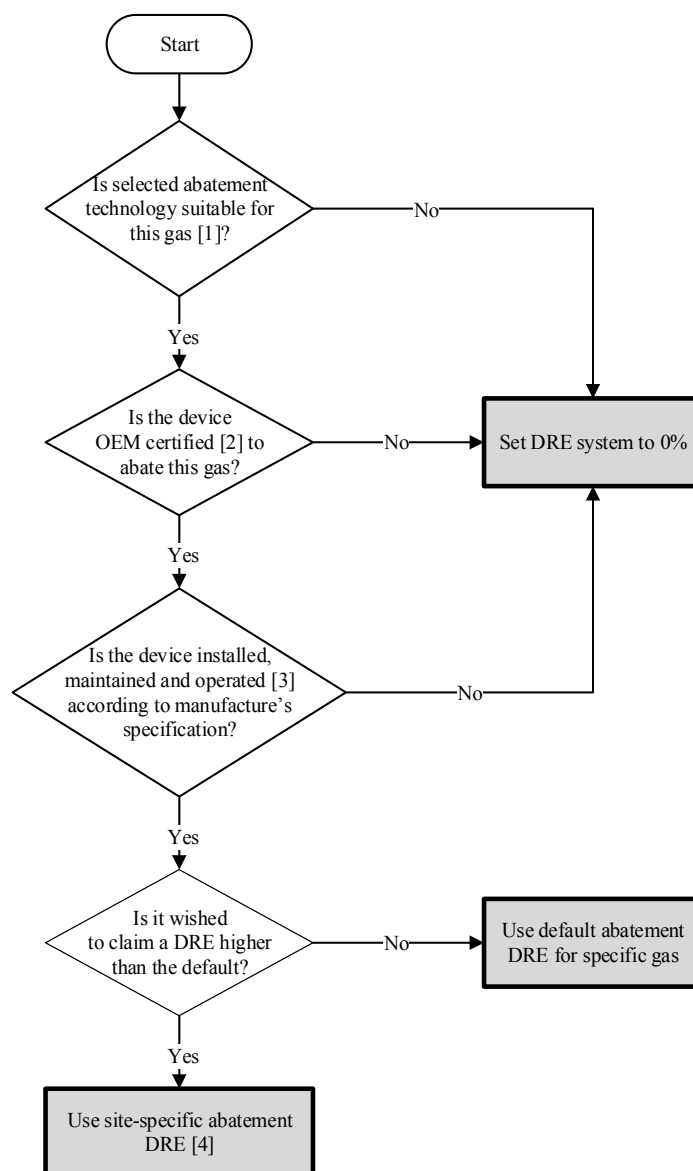
It is recognised that since the 2006 Guidelines, the varying performance of different abatement technologies needs to be accounted for (six being listed in the table below), both in terms of their emission reduction efficiencies ("Destruction Removal Efficiency", DRE) and their propensity to convert hydrocarbon fuel (such as methane or propane) into CF<sub>4</sub> by direct reaction with fluorine that is exhausted from CVD process tools during chamber cleaning; this fluorine typically originating from NF<sub>3</sub>. This detail needs capture without unnecessarily complicating the table and awaits data capture and analysis. Preliminary data is presented.

**Table 6.6A Destruction Reaction Efficiency (DRE) of PFC Abatement Technologies (X=Suitable to use default DRE)]**

TABLE 6.6A PFC GASES																	
Abatement Technology	PFC Gases																
	CF <sub>4</sub>	C <sub>3</sub> F <sub>6</sub>	C <sub>4</sub> F <sub>6</sub>	C <sub>4</sub> F <sub>8</sub>	C <sub>3</sub> F <sub>8</sub>	CHF <sub>3</sub>	CH <sub>2</sub> F <sub>2</sub>	C <sub>4</sub> F <sub>6</sub>	C <sub>5</sub> F <sub>8</sub>	C <sub>2</sub> H <sub>5</sub> F	C <sub>3</sub> F <sub>6</sub> O	C <sub>4</sub> F <sub>6</sub> O	CH <sub>3</sub> F	C <sub>2</sub> F <sub>4</sub>	COF <sub>2</sub>	NF <sub>3</sub>	SF <sub>6</sub>
Cartridge				X		X										X	X
Hot-wet < 800° C																	
Hot-wet > 800° C																	
Plasma	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
Catalyst	X															X	

[This table to be followed by default DRE values on a per gas or per process type (as currently in IPCC 2006 but with updated defaults) or per gas and process (etch vs. cleans) basis].



**Figure 6.3 Decision Tree for PFC Abatement Default Emission Factors****Notes:**

1. The abatement device is deemed suitable according to the Applicability of PFC Abatement Technologies table.
  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, etc.
  4. The appropriate test method must be used (EPA, ISMI or similar accounting for dilution) and at a frequency of at least 5% annually.
- [As regards 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 such as pump purges.
- If the abatement device is deemed suitable but is not performing up to the default DRE, consider adding another decision point before setting DRE to 0% in the case the facility wants to add a site-specific DRE value lower than the default but greater than 0% (when the abatement device is not certified or installed operated in accordance with the OEM specs)].

<b>TABLE 6.6B</b> <b>TIER 2A&amp;2B DEFAULT EFFICIENCY PARAMETERS FOR ELECTRONICS INDUSTRY FC EMISSION REDUCTION TECHNOLOGIES</b>							
Emission Control Technology	CF <sub>4</sub>	C <sub>2</sub> F <sub>6</sub>	CHF <sub>3</sub>	C <sub>3</sub> F <sub>8</sub>	c-C <sub>4</sub> F <sub>8</sub>	NF <sub>3</sub>	SF <sub>6</sub>
d <sub>i</sub>							
Notes:							

### 6.2.2.2 HEAT TRANSFER FLUIDS

[Work in progress]

## 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)<sup>6</sup>. 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-FPD manufacturing.

Table 6.7 of the 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-FPD manufacturing plants are not operated at design capacities for sustained periods, such as a full year. Instead, the capacity 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 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-FPD 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<sub>u</sub> (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<sub>PV</sub> in Equation 6.1). [Because recent surveys indicate that between 40 – 50 percent of PV manufacture actually uses FC, and the usage trend may be increasing, the recommended default value for C<sub>PV</sub> is 0.5 (value to be updated)].

<sup>6</sup> 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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## **6.2.4 Completeness**

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

## **6.3.2 Activity data uncertainty**

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

## **6.4.2 Reporting and documentation**

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

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