CHAPTER 1

INTRODUCTION

Authors

Bofeng Cai (China) and Deborah A. Ottinger (USA)

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1 INTRODUCTION

Users are expected to go to Mapping Tables in Annex 5, before reading this chapter. This is required to correctly understand both the refinements made and how the elements in this chapter relate to the corresponding chapter in the 2006 IPCC Guidelines.

1.1 INTRODUCTION

This volume, Industrial Processes and Product Use (IPPU), covers greenhouse gas emissions occurring from industrial processes, from the use of greenhouse gases in products, and from non-energy uses of fossil fuel carbon. The former section 'Solvent and Other Product Use' in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* has been incorporated in this volume.

Greenhouse gas emissions are produced from a wide variety of industrial activities. The main emission sources are releases from industrial processes that chemically or physically transform materials. (Examples include the blast furnace in the iron and steel industry, ammonia and other chemical products manufactured from fossil fuels used as chemical feedstock, the cement industry, aluminium production, and HCFC-22 production). During these processes, many different greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and other fluorinated compounds such as trifluoromethyl sulphur pentafluoride (SF_5CF_3) can be produced and emitted.

In addition, greenhouse gases often are used in products such as refrigerators, foams or aerosol cans. For example, HFCs are used as alternatives to ozone depleting substances (ODS) in various types of product applications. Similarly, sulphur hexafluoride (SF_6) and N_2O are used in a number of products used in industry (e.g., SF_6 used in electrical equipment, N_2O used as a propellant in aerosol products primarily in food industry) or by end-consumers (e.g., SF_6 used in running-shoes, N_2O used during anaesthesia). A notable feature of these product uses is that, in almost all cases, significant time can elapse between the manufacture of the product and the release of the greenhouse gas. The delay can vary from a few weeks (e.g., for aerosol cans) to several decades as in the case of rigid foams. (See Section 1.5 and Chapters 7 and 8 for discussions of the methodological issues associated with this delay.) In some applications (e.g., refrigeration) a fraction of the greenhouse gases used in the products can be recovered at the end of product's life and either recycled or destroyed. In addition, HFCs, PFCs, SF_6, NF_3, and several other fluorinated greenhouse gases may be used in and/or emitted by processes such as electronics manufacturing. Other fluorinated greenhouse gases[1] that are used in such processes, that are not covered by Annexes A through E of the Montreal Protocol, and that have had their global warming potentials (GWPs) listed in IPCC Assessment Reports include, for example:

- halogenated ethers and perfluoropolyethers used for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering during electronics manufacturing and other processes. (e.g., HFE-449s1, HFE-569sf2, and PFPMIE)[2] (see Table 6.5 of this volume for a more complete list);
- fluoroketones;
- and other halocarbons not covered by Annexes A through E of the Montreal Protocol including, for example CF_3I, CH_2Br_2, $CHCl_3$, CH_3Cl, CH_2Cl_2.

This volume of the *2019 Refinement* also provides estimation methods for halogenated greenhouse gases which are not covered by Annexes A through E of the Montreal Protocol and for which GWP values were not available from an IPCC Assessment Report at the time the *2019 Refinement* was developed. Examples of such GHGs include:

- c-C_4F_8O;
- perfluorotripropylamine, perfluoromethylmorpholine, 3-ethoxy-1,1,1,2,3,4,4,5,5,6,6,6-dodecafluoro-2-trifluoromethyl-hexane, and other fluorinated liquids used for temperature control, device testing, cleaning

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[1] Some of these compounds are liquid at room temperature but enter the atmosphere through evaporation, particularly when used at high temperatures, as many of them are.

[2] The first two compounds are hydrofluoroethers marketed under the Novec^{TM} Engineered Fluid tradename by 3M^{TM}. The last compound, PFPMIE, is marketed under the Galden^{TM} tradename by Solvay.

substrate surfaces and other parts, and soldering during electronics manufacturing and other processes (see Table 6.5 for a more complete list)[3];

- fluoronitriles.

Product use is combined with the industrial process guidance because in many cases production and import/export data are needed to estimate emissions in products and because product use may also occur as part of industrial activities, apart from the non-industrial sectors (retail, services, households.) It is therefore desirable to link estimation of emissions associated with production and product use. The non-energy uses of fossil fuels encompass their uses as feedstock, reductants and as non-energy products in which their physical properties are used directly rather than combusted for energy purposes.

This chapter presents:

- the definition and structure of the treatment of industrial processes and product use (1.1);
- a number of general or cross-cutting issues (1.2), among which are the definition of industrial process and fuel combustion emissions (1.2.1) and sources of international data (1.2.5);
- the nature of non-energy uses of fossil fuels (1.3);
- the completeness and allocation of CO_2 from non-energy use of fuels (1.4); and
- the choice between the mass-balance and emission-factor approaches (1.5) with specific relevance to the fluorinated gases covered in Chapters 7 and 8 of this volume.

SECTOR CLASSIFICATION AND STRUCTURE

Figure 1.1 sets out the structure and classification codes for each category and subcategory for the IPPU Sector. In the *2019 Refinement*, Figure 1.1 has been updated by (1) adding subcategories for Hydrogen Production (2B10), Rare Earths Production (2C7), Micro electrical mechanical Systems (2E4), and Waterproofing of Electronic Circuits (2G2c) to reflect the addition of new guidance for these subcategories; (2) adding several subcategories under Fluorochemical Production to reflect the broad range of fluorochemical products, (3) updating the name of the Electronics subcategory previously called “TFT Flat Panel Display” to the more comprehensive “Display,” and (4) removing the subcategory “Heat Transfer Fluid” from the Electronics category, because the fluorinated liquids previously covered by this subcategory may be used in any of the Electronics sub-sectors (Semiconductors, Displays, Photovoltaics, or microelectromechanical systems (MEMS)), may be used for applications other than heat transfer (including for testing, soldering, and cleaning), and are identifiable through their chemical contents, which are reported based on the columns of Table 1.1 (see note 10 to Table 1.1).

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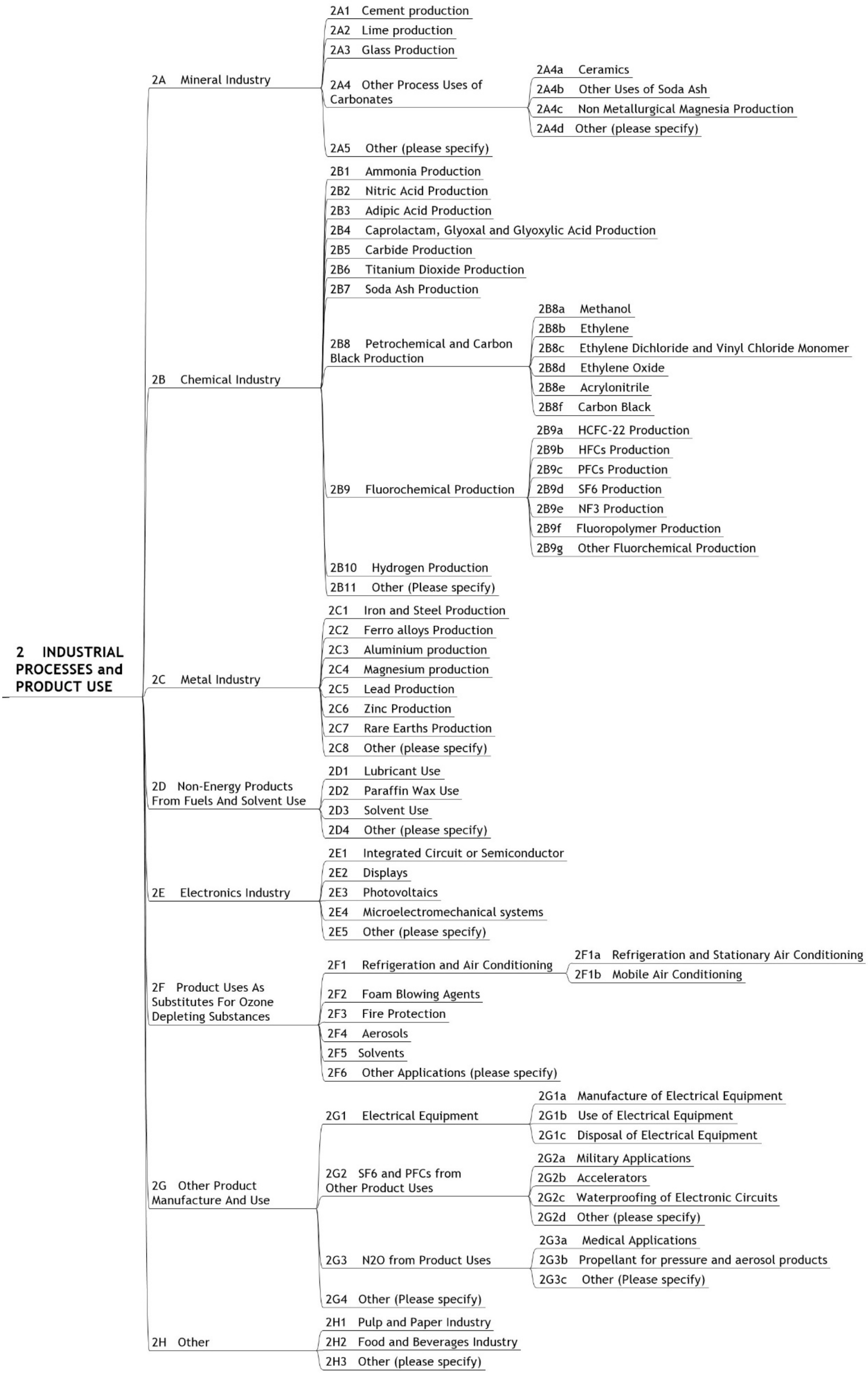
[3] The first two compounds are marketed under the Fluorinert™ trade name, along with other fully fluorinated compounds such as alkanes, other tertiary amines and aminoethers. The last compound is marketed under the Novec Engineered Fluid™ tradename.

Figure 1.1 (Updated) Industrial Processes and Product Use categories



1.2 GENERAL AND CROSS-CUTTING ISSUES

1.2.1 Definition of industrial process, fuel combustion and fuel transformation emissions

Allocating emissions from the use of fossil fuel between the Energy and IPPU Sectors can be complex. The feedstock and reductant uses of fuels frequently produce gases that may be combusted to provide energy for the process. Equally part of the feedstock may be combusted directly for heat (Sector 1A) or transformed into other energy products (Sector 1B). This can lead to uncertainty and ambiguity in reporting. To help to overcome this problem, these *Guidelines* introduce practical guidance on when to allocate CO_2 emissions released from combustion of fuel to the subcategory fuel combustion within the energy source category or to the industrial process source category. The rule is given in Box 1.1.

Further guidance for specific source categories is also presented in the *2019 Refinement* (including the revised guidance on coke production and new guidance for hydrogen production), to include cross-references to the relevant methodology sections of the Energy Volume, and to present *good practice* for reporting allocations.

The problems encountered when allocating CO_2 emissions to fuel combustion, fuel transformation or industrial processes are particularly prominent when by-product fuels or waste gases are transferred from the manufacturing site and combusted elsewhere in quite different activities. This fact has formed the principle for the guidance given in Box 1.1, which provides a definition for fuel combustion and a criterion for deciding whether emissions from by-product fuels should be reported in the IPPU Sector or in an Energy Sector source category. Section 1.3 provides background information on the nature of non-energy uses of fossil fuels, accounting for feedstock and reductant uses of fossil fuels and on the links with the fossil fuel use in the Energy Sector.

1.2.2 Capture and abatement

No refinement.

1.2.3 Precursors

No refinement.

1.2.4 Indirect N_2O

No refinement.

1.2.5 International data sources

Good national data are to be preferred and used wherever available. In cases where data availability is a problem, inventory compilers may consult international data sources for proxy data for IPPU estimates. Sources include:

- United Nations (UN) industrial production statistics which are available in hard copy in the ‘Industrial Commodity Statistics Yearbook’ (UN, 2004) from 1991 onwards and as CD-ROM with statistics from 1950 onwards; data (in physical units) are given by commodity and country for all years and almost all commodities relevant for emission inventories.
- Organisation for Economic Co-operation and Development (OECD) publishes production data in monetary units (value of production) for the OECD countries (http://www.oecd.org/statsportal/0,2639,en_2825_293564_1_1_1_1_1,00.html) but data for the most recent years are not available. OECD also sells a publication with additional data (http://www.oecd.org/document/63/0,2340,en_2825_499554_1935935_1_1_1_1,00.html), but according to the web site the most recent data are for 2001. National account data can be also accessed, for a charge, for the years up to 2002. Most useful is perhaps the STAN (Industry Structural Analysis) database of the OECD (again only available via subscription at http://hermia.sourceoecd.org/vl=4126925/cl=58/nw=1/rpsv/cw/vhosts/oecdstats/16081307/v265n1/contp1-1.htm), this contains monetary production data, for years up to 2002, for major industries. Note, however, that the monetary value reflects not only the production quantity but also the price of the product - which may fluctuate from one year to another - so the data should be used with care.

- Eurostat publishes PRODCOM data (Eurostat, 2005) for many European countries.
- Statistics on production of a large number of commodities and capacity of individual plants are provided by the commodity and country by the U.S. Geological Survey as part of the International Minerals Statistics and Information (USGS, 2005).

TABLE 1.1 (UPDATED)
INDUSTRIAL PROCESSES AND PRODUCT USE CATEGORIES AND THEIR POSSIBLE EMISSIONS

2 Industrial Processes and Product Use (Note 1, 2)	CO_2	CH_4	N_2O	HFCs	PFCs	SF_6	NF_3	Other halogenated compounds (Note3)
2A Mineral Industry								
2A1: Cement Production	X	*						
2A2: Lime Production	X	*						
2A3: Glass Production	X	*						
2A4: Other Process Uses of Carbonates								
2A4a: Ceramics	X	*						
2A4b: Other Uses of Soda Ash	X	*						
2A4c: Non Metallurgical Magnesia Production	X	*						
2A4d: Other	X	*						
2A5: Other	X	*	*					
2B Chemical Industry								
2B1: Ammonia Production	X	*	*					
2B2: Nitric Acid Production	*	*	X					
2B3: Adipic Acid Production	*	*	X					
2B4: Caprolactam, Glyoxal and Glyoxylic Acid Production	*	*	X					
2B5: Carbide Production	X	X	*					
2B6: Titanium Dioxide Production	X	*	*					
2B7: Soda Ash Production	X	*	*					
2B8: Petrochemical and Carbon Black Production								
2B8a: Methanol	X	X	*					
2B8b: Ethylene	X	X	*					
2B8c: Ethylene Dichloride and Vinyl Chloride Monomer	X	X	*					
2B8d: Ethylene Oxide	X	X	*					
2B8e: Acrylonitrile	X	X	*					
2B8f: Carbon Black	X	X	*					
2B9: Fluorochemical Production (Note 4)								
2B9a: HCFC-22 Production				X	X			X
2B9b: HFC Production				X	X			*
2B9c: PFC Production				X	X			*
2B9d: SF6 Production						X		
2B9e: NF3 Production			X		X		X	
2B9f: Fluoropolymer Production				X	X			X
2B9g: Other Fluorochemical Production (Note 5)				X	X	X	X	X
2B10: Hydrogen	X	*	*					
2B11: Other	*	*	*	*	*	*		*
2C Metal Industry								
2C1: Iron and Steel Production	X	X	*					
2C2: Ferroalloys Production	X	X	*					
2C3: Aluminium Production	X	*			X			
2C4: Magnesium Production (Note 6)	X			X	X	X		X
2C5: Lead Production	X							
2C6: Zinc Production	X							
2C7: Rare Earths Production	X				X			
2C8: Other	*	*	*	*	*	*		*
2D Non-Energy Products from Fuels and Solvent Use (Note 7)								
2D1: Lubricant Use	X							
2D2: Paraffin Wax Use	X	*	*					
2D3: Solvent Use (Note 8)								
2D4: Other (Note 9)	*	*	*					
2E Electronics Industry								
2E1: Integrated Circuit or Semiconductor (Note 10)	*		X	X	X	X	X	X
2E2: Display (Note 10)			X	X	X	X	X	X
2E3: Photovoltaics (Note 10)			X	X	X	X	X	X
2E4: MEMS (Note 10)			X	X	X	X	X	X
2E5: Other	*	*	*	*	*	*		*

TABLE 1.1 (UPDATED) (CONTINUED)
INDUSTRIAL PROCESSES AND PRODUCT USE CATEGORIES AND THEIR POSSIBLE EMISSIONS

2 Industrial Processes and Product Use (Note 1, 2)	CO_2	CH_4	N_2O	HFCs	PFCs	SF_6	NF_3	Other halogenated compounds (Note3)
2F Product Uses as Substitutes for Ozone Depleting Substances								
2F1: Refrigeration and Air Conditioning								
2F1a: Refrigeration and Stationary Air Conditioning	*			X	X			*
2F1b: Mobile Air Conditioning	*			X	X			*
2F2: Foam Blowing Agents	*			X	*			*
2F3: Fire Protection	*			X	X			*
2F4: Aerosols				X	X			*
2F5: Solvents (Note 11)				X	X			*
2F6: Other Applications	*	*	*	X	X			*
2G Other Product Manufacture and Use								
2G1: Electrical Equipment								
2G1a: Manufacture of Electrical Equipment (Note 12)					X	X		X
2G1b: Use of Electrical Equipment (Note 12)					X	X		X
2G1c: Disposal of Electrical Equipment (Note 12)					X	X		X
2G2: SF_6 and PFCs from Other Product Uses								
2G2a: Military Applications(Note 13)					X	X		X
2G2b: Accelerators (Note 14)					*	X		X
2G2c: Waterproofing of Electronic Circuits				X	X			
2G2d: Other(Note 15)				X	X	X		
2G3: N_2O from Product Uses								
2G3a: Medical Applications			X					
2G3b: Propellant for Pressure and Aerosol Products			X					
2G3c: Other			X					
2G4: Other	*	*		*				*
2H Other								
2H1: Pulp and Paper Industry (Note 16)	*	*						
2H2: Food and Beverages Industry (Note 16)	*	*						
2H3: Other	*	*	*					

1) 'X' denotes gases for which methodological guidance is provided in this volume.
2) '*' denotes gases for which emissions may occur but for which no methodological guidance is provided in this volume.
3) For precursors (NOx, CO, NMVOC, SO_2 and NH_3) see Table 7.1 in Chapter 7 of Volume 1.
4) The Tier 2 and 3 methodologies are applicable to any fluorinated greenhouse gas, including those specifically listed in the columns above and other fluorinated compounds. In these tiers all estimates are based on measurements, either measured losses from the process or measured emissions, and accommodate process-specific releases. For the Tier 1 methodology, default emission factors (for the product and/or by-products) are provided specifically for production of HCFC-22, SF_6 and NF_3. For the production of HFCs, PFCs, and other fluorochemicals, a Tier 1 default emission factor based on a wide range of fluorochemical products and processes is provided. In addition, a representative combination of emitted HFCs and PFCs is provided for situations when the inventory compiler does not know the chemical identities of the emitted gases.
5) The 'Other halogenated gases' include but are not limited to fluorinated ethers, perfluoropolyethers, fluoroketones, fluorinated alcohols, SF_5CF_3, and perfluoroamines.
6) Small amounts of CO_2 used as a diluent for SF_6 and emitted during magnesium processing is considered insignificant and is usually counted elsewhere. The 'other halogenated gases' here mainly comprise fluorinated ketones.
7) Emissions from feedstock uses in petrochemical industry should be addressed in 2B8 (Petrochemical and Carbon Black Production). Emissions from some product uses should be allocated to each industry source category (e.g., CO_2 from carbon anodes and electrodes → 2C (Metal Industry)).
8) Only NMVOC emissions and no direct greenhouse gases are relevant to this category. Therefore no methodological guidance is provided in this volume. For guidance on NMVOC, see Chapter 7, Volume 1.
9) Emissions from Asphalt Production, Paving of Roads and Roofing are included here. For details, see Section 5.4 of this volume.
10) The 'Other halogenated compounds' may include, for example, c-C_4F_8O, as well as hydrofluoroethers, perfluoropolyethers, perfluoroamines, and perfluoroalkyl morpholines used for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering during electronics manufacturing. Specific compounds to be reported here include (but are not limited to) those listed in Table 6.5 of Volume 3, such as HFE-449s1 (3M^{TM} Novec^{TM} HFE-7100), HFE-569sf2, (3MTM Novec^{TM} HFE-7200), perfluorotripropylamine (PTPA, 3M^{TM} Fluorinert^{TM} FC-3283/FC-8270), perfluoroisopropylmorpholine (3M^{TM} Fluorinert^{TM} FC-770), and various PFPMIE fractions marketed by Solvay^{TM} under the Galden^{TM} trademark, such as HT-55 through HT-270. See Volume 3, Chapter 6 for more potentially emitted compounds.
11) Emissions from use of fluorinated gases as solvent should be reported here. Emissions from aerosols containing solvents should be reported under Category 2F4 rather than under this category. Emissions from other solvent use should be reported under 2D3.
12) 'Other halogenated gases' may include fluoroketones and fluoronitriles.
13) 'Other halogenated gases' may include, for example, hydrofluoroethers, perfluoropolyethers, perfluoroamines, and perfluoroalkyl morpholines used for temperature control and other applications. Specific compounds to be reported here include (but are not limited to) those listed in Table 6.5 of Volume 3.
14) 'Other halogenated gases' may include fluoroketones and fluoronitriles.
15) Appendix 1 of this volume includes a basis for future methodological development for estimating fluorinated GHG emissions from the textile, carpet, leather, and paper industries. Gases that are believed to be emitted from these industries include HFCs, PFCs, SF_6, and potentially other fluorinated GHGs.

16) No specific section on these categories is provided in this volume, but methodological guidance on CO_2 emissions from use of carbonates from these industries is provided in Chapter 2, Section 2.5 of this volume.

1.3 NATURE OF NON-ENERGY USES OF FUELS

As explained in Section 1.1 some CO_2 emissions from fossil fuels arise from uses that are not primarily for energy purposes and, in this section, the principles are described which have guided their estimation and reporting. The methods used to estimate emissions are described in the specific IPPU source category chapters (Chapters 3, 4 and 5). This section provides important and additional background information for the use of data relating to non-energy use and the links between these data and the fossil fuel use.

Non-energy use is widespread, diverse and the correct reporting of its emissions is conceptually difficult. It is *good practice* to ensure that all fossil fuels supplied for non-energy purposes can be linked to uses covered by the inventory and the reported emissions are consistent with the carbon supplied. Accordingly, Section 1.4 provides guidance for assessing consistency and completeness of carbon emissions from feedstock use of fuels by (a) checking that feedstock requirements of processes included in the inventory are in balance with the feedstock supply as recorded in national energy statistics, (b) checking that total reported bottom-up calculated CO_2 emissions from feedstock sources at different subcategory levels are complete and consistent, (c) documenting and reporting how these emissions are allocated in the inventory.

Note that in the *2019 Refinement*, new methods are presented to reflect the use of bio-fuels and biomass in non-energy applications, for example as feedstock in the production of hydrogen (see Section 3.11). These IPPU processes may generate methane or nitrous oxide for inclusion within the national inventory total, and also generate IPPU bio-CO_2 emissions as a memo item to the national inventory. The principles outlined in this section, whilst primarily developed to account for fossil carbon across the Energy and IPPU sectors, equally can be applied to reconcile inventory NEU and energy use data for biofuels against national commodity balance data.

1.3.1 Types of uses

Some primary fuels (coal, natural gas) and secondary fuels derived from coal and crude oil may be used for non-fuel purposes. These are commonly referred to as non-energy use of fuels although their use may involve combustion of part of the hydrocarbon content for heat-raising.

Three categories of non-energy use can be distinguished depending on its use:

1. *Feedstock*: Feedstocks are fossil fuels that are used as raw materials in chemical conversion processes in order to produce primarily organic chemicals and, to a lesser extent, inorganic chemicals (especially ammonia) and their derivatives (OECD/IEA/Eurostat, 2004). In most cases, part of the carbon remains embodied in the product manufactured. The use of hydrocarbon feedstocks in chemical conversion processes is almost entirely confined to the chemical and petrochemical industries.

2. *Reductant*: Carbon is used as reducing agent for the production of various metals (Chapter 4) and inorganic products (Sections 3.6 – 3.8). It is either used directly as reducing agent or indirectly via the intermediate production of electrodes used for electrolysis. In most cases, only very small amounts of carbon are embodied in the product manufactured, while the major part is oxidised during the reduction process.

3. *Non-energy product*: Apart from fuels, refineries and also coke ovens produce some non-energy products which are used directly (i.e., without chemical conversion) for their physical or diluent properties or which are sold to the chemical industry as chemical intermediate. Lubricants and greases are used in engines for their lubricating properties; paraffin waxes are used as candles, for paper coating etc.; bitumen on roofs and roads for its waterproofing and wear qualities. Refineries also produce white spirits, which are used for their solvent properties.

This chapter discusses emissions that result from the first use of the hydrocarbons belonging to these three categories. Table 1.2 shows the types of hydrocarbons used in the three categories and the main applications. The list of fuel types and processes is illustrative and not exhaustive as some lesser uses of refinery or coke oven products are omitted. For example, refinery olefins are not shown because only a minor portion of the olefins used for the manufacture of intermediate products is produced in refineries.

This section focuses on the issues surrounding the reporting of industrial process and fuel combustion emissions from the use of fossil fuels as feedstocks and reductants (the first and second categories in Table 1.2). The relatively simpler issues affecting estimation of emissions from the first uses of non-energy products (the third category in Table 1.2) are presented with the methods in Chapter 5.

In addition to the emissions from the first use of hydrocarbons, products made from feedstocks (methanol, ethylene, carbon black) and their derivatives may lead to additional emissions after manufacture and sale. For example, the conversion of ethylene to ethylene oxide leads to substantial industrial process CO_2 emissions (Section 3.9).

Emissions from subsequent uses of 'used' non-energy products (post-consumer waste) are not included in this volume on IPPU Sector but are covered under the Energy and Waste Sectors depending on whether the treatment occurs with or without energy recovery or in the form of wastewater treatment.

TABLE 1.2 (UPDATED)
TYPES OF USE AND EXAMPLES OF FUELS USED FOR NON-ENERGY APPLICATIONS

Type of use	Example of fuel types	Product/process	Chapter
Feedstock	natural gas, oils, coal	ammonia	3.2
	natural gas, oils, coal, biofuels, biomass	hydrogen	3.11
	naphtha, natural gas, ethane, propane, butane, gas oil, fuel oils	methanol, olefins (ethylene, propylene), carbon black	3.9
Reductant	petroleum coke	carbides	3.6
	coal, petroleum coke	titanium dioxide	3.7
	metallurgical cokes, pulverised coal, natural gas	iron and steel (primary)	4.2
	metallurgical cokes	ferroalloys	4.3
	petroleum coke, pitch (anodes)	aluminium 1	4.4
	petroleum coke, pitch (anodes)	Rare Earths Production	4.8
	metallurgical coke, coal	lead	4.6
	metallurgical coke, coal	zinc	4.7
Non-energy product	lubricants	lubricating properties	5.2
	paraffin waxes	misc. (e.g., candles, coating)	5.3
	bitumen (asphalt)	road paving and roofing	5.4
	white spirit2, some aromatics	as solvent (paint, dry cleaning)	5.5

[1.] Also used in secondary steel production (in electric arc furnaces) (see Chapter 4.2).

[2.] Also known as mineral turpentine, petroleum spirits, industrial spirit ('SBP').

1.3.2 Accounting for feedstock and reductant uses of fossil fuels and their CO_2 emissions

No refinement.

1.3.3 Emissions from refinery processes

Refineries manufacture petroleum products for fuel and for non-energy uses, and in doing so produce hydrogen and other gases, intermediate products and basic chemicals. The CO_2 emissions from fuel consumed by the refinery for this activity are reported as Energy Sector emissions. This principle is maintained in the *Guidelines* even when some fuel use in the refinery is to support manufacture of chemicals for sale (for example, propylene or aromatics). In the *2019 Refinement*, this principle is re-iterated within the new guidance presented for hydrogen production, which is a new IPPU source category; the emissions from hydrogen production within a refinery as an intermediate product are primarily to support Energy sector activities, with emissions to be reported in the Energy sector.

The manufacture of basic chemicals in refineries is a normal occurrence usually through the treatment of by-products of mainstream manufacture and they may be used in other refinery processes or transferred to adjoining petrochemical works. However, in some circumstances the demand for basic chemicals may cause the refinery to adjust production processes to increase supply of the chemical and sell directly into the market. Despite this activity the fuel use to support all processes is still considered as refinery fuel and the emissions as Energy Sector emissions. It is important to recognise that the production for sale of basic chemicals in refineries is considered a secondary activity distinct from the manufacture of chemicals in adjoining or co-located petrochemical works. This is consistent with the separate statistical classification of the two economic activities.

1.4 QC OF COMPLETENESS AND ALLOCATION OF CO_2 FROM NON-ENERGY USES

1.4.1 Introduction

No refinement.

1.4.2 Scope of methods

No refinement.

1.4.3 Quality control of completeness

The *CO_2 completeness check* (Section 1.4.3.1) starts from energy balance data and is designed to check that all significant emissions of CO_2 from the first non-energy uses of fossil fuels are reported somewhere in the inventory, without double counting. The emissions are the sum of CO_2 emissions from (a) fuels used as feedstock in the chemical industry, (b) fuels used as reductant in the metal industry, (c) fuel products oxidised during use (partly or fully; direct emissions or emissions of carbon containing non-CO_2 gases (Non-methane volatile organic compound (NMVOC), carbon monoxide (CO) and CH_4) oxidised in the atmosphere).

Subsequent CO_2 emissions may occur in the waste phase if the waste oils or waste products are incinerated. However, the amount of fossil-carbon containing products disposed of annually as waste is not equal to the amount used annually for first uses because fossil-carbon containing products may be imported or exported or they may be used for several years before they are discarded. The complications which arise from external trade hold equally for emissions resulting from the use of products made from feedstocks and their derivatives. Since derivative products may also be imported or exported the emissions from their use (e.g., from ethylene oxide or acrylonitrile production) cannot be linked directly to the first non-energy use of fossil fuels. For these reasons the *CO_2 completeness check* is limited to the first non-energy uses of fossil carbon which lead to emissions and does not include CO_2 emissions from waste incineration. Other non-energy sources of fossil CO_2 are flaring, venting and other fugitive emissions in the Category 1B and are also excluded from this completeness checking method.

The *feedstock balance check* (Section 1.4.3.2) is simpler in concept and starts from non-energy statistics for feedstock/reductant supplies and compares them with the reported (or implied) requirements for feedstock by the various IPPU processes. This check identifies discrepancies between the two sets of data that may indicate omitted processes or feedstock use classified as fuel combustion.

1.4.3.1 CO_2 COMPLETENESS CHECK

The principle of this method is based on comparisons of reported CO_2 emissions with potential CO_2 emissions from the fuel for non-energy uses and consists of three steps:

1. CO_2-equivalent carbon contents are calculated for the non-energy use of fossil fuels as reported in national energy statistics (including the coke and other solid fuel inputs into blast furnaces).
2. Total CO_2 emissions reported per IPPU subcategory are related to (main) fuels used for non-energy purposes. This should include emissions from by-product fuels transferred from the IPPU Sector and reported elsewhere in the Energy Sector.
3. Total reported fossil IPPU CO_2 emissions are compared with a top-down estimate of potential CO_2 of the carbon content of the feedstocks used. The comparison is made by calculating the actual CO_2 released as a fraction of the total potential CO_2 in the input fuels. The fractions may then be compared with values observed for different industries (see below, ‘Step 3: Actions arising from the comparison’). In case of significant discrepancies, likely causes of differences should be listed, taking into account the accuracy of the allocation of sources to individual fuels.

Step 1: Feedstock amount and CO_2-equivalent carbon content

The amount of feedstock and non-energy use entered in Table 1.3 is the final consumption of each fuel for 'non-energy' purposes as reported in the national energy statistics. The quantities should be expressed in, or converted to, Terajoules (TJ) using the net calorific (lower heating) values (see Chapter 1 of Volume 2 for IPCC default values). Next the potential CO_2-eq. emissions associated with the carbon contents can be calculated using country-specific or IPCC default carbon content values (see Chapter 1 of Volume 2 for IPCC default values).

If a country accounts separately for the production of by-product gases from chemical production processes in their energy statistics, these should also be added in the top row of fuel amounts associated with feedstock emissions of CO_2 and the corresponding amount of CO_2-eq. calculated using country-specific carbon content values.

Step 2: Allocating source category CO_2 emissions to one or more feedstock fuels

The CO_2 emissions reported in the IPPU Sector that arise mainly from the metal and chemical industries, should be allocated to the corresponding fuel types used as input for the process. Emissions resulting from the non-energy use of fossil fuels reported elsewhere should be included here too. Guidance for this allocation is provided in Table 1.3, where for each subcategory the most common feedstock fuel is marked as a bolded box. Other fuels that are known to be used as feedstock for these sources are indicated with a regular box. In most cases these boxes are the only allocations to be checked for the country-specific application. If no specific information is available, all CO_2 emissions may be assigned to the bold box. Where country-specific information shows that several fuels are used as feedstock, either the specific fractions for each fuel can be used or each may be given an equal share of the source total.

Step 3: Actions arising from the comparison

The fraction of potential CO_2 actually released may be calculated per fuel type or per group of fuels, and can be assessed for their level, trend and interannual variation. The values of the fractions may be compared with values inferred from the information provided for the methodological tiers for the source categories or from literature (e.g., Neelis *et al.*, 2005).

Small differences or changes may be expected due to process-specific technological or operational differences. Major differences can arise from large differences in technologies or, when comparing with other countries' data or literature, from the use of a different definition of feedstocks (for details see Section 1.3). A third explanation of discrepancies may be due to errors in the presumed allocation of source category emissions to specific fuel types used as feedstock in the process.

TABLE 1.3 (UPDATED) VERIFICATION OF COMPLETENESS OF REPORTED CO_2 FROM NON-ENERGY USE OF FOSSIL FUELS

NOTES							**Solids**						
1	Year:_________					Unit	Coal	Coke	Coal tars	Coal oils	BF/OF gas	(CO gas) b)	Total solids
2	A: Declared NEU (from commodity balance)					TJ							
3	B: Carbon Content					kg C/GJ							
	C: Total supplied for feedstock/non-energy	[C = A * B / 1000]				Gg C							
4	**D: Total supplied for feedstock/non-energy**	**[D = C * 44/12]**				Gg CO_2-eq.							
5	**E: Implied carbon fraction oxidised**	**[E = F / D * 100]**				%							
			Activity a)	CO_2 Emissions a)	IEF CO_2								
6	**F: Total fossil IPPU CO_2 reported**					Gg CO_2							
	2 INDUSTRIAL PROCESSES					Gg CO_2							
7	**2A: Mineral Industry**					Gg CO_2							
	(Please specify the subcategory.)					Gg CO_2							
7	**2B: Chemical Industry**					Gg CO_2							
	2B1: Ammonia Production					Gg CO_2							
	2B5: Carbide Production					Gg CO_2							
	2B6: Titanium Dioxide Production					Gg CO_2							
	2B8: Petrochemical and Carbon Black Production					Gg CO_2							
	2B8a: Methanol					Gg CO_2							
	2B8b: Ethylene					Gg CO_2							
	2B8f: Carbon Black					Gg CO_2							
	2B10: Hydrogen					Gg CO_2							
	2B11: Other					Gg CO_2							
7	**2C: Metal Industry**					Gg CO_2							
	2C1: Iron and Steel Production					Gg CO_2							
	2C2: Ferroalloys Production					Gg CO_2							
	2C3: Aluminium Production					Gg CO_2							
	2C5: Lead Production					Gg CO_2							
	2C6: Zinc Production					Gg CO_2							
	2C7: Rare Earths Production					Gg CO_2							
	2C8: Other					Gg CO_2							
7	**2D: Non-Energy Products from Fuels and Solvent Use**					Gg CO_2							
	2D1: Lubricant Use					Gg CO_2							
	2D2: Paraffin Wax Use					Gg CO_2							
	2D3: Solvent Use					Gg CO_2							
	2D4: Other					Gg CO_2							
7	**2H: Other**					Gg CO_2							
	2H1: Pulp and Paper Industry					Gg CO_2							
	2H2: Food and Beverage Industry					Gg CO_2							
	2F3: Other					Gg CO_2							
	EXCEPTIONS REPORTED ELSEWHERE					Gg CO_2							
7	**1A FUEL COMBUSTION ACTIVITIES**					Gg CO_2							
	1A1a: Main Activity Electricity and Heat Production					Gg CO_2							
	1A1b: Petroleum Refining					Gg CO_2							
	1A1c: Manufacture of Solid Fuels and Other Energy Industries					Gg CO_2							
	1A2: Manufacturing Industries and Construction					Gg CO_2							

a) Same Activity Data and emissions as in sectoral background table (also for Activity Data NE, NO, C, and for emissions NE, NO, IE, where applicable).

b) To be included only if coke production is reported as part of integrated iron and steel production.

1: To be specified per year

2: Cf. Auxiliary worksheet for CO2-Reference Approach to subtract the NEU from total apparent consumption

3: IPCC default or country-specific values

4: So-called potential emissions, i.e., carbon embodied in the feedstock/non-energy fuels expressed in CO_2-eq.

5: Ratio of CO_2 emissions (direct emissions as well as atmospheric inputs of CO_2 from other carbon (non-CO_2)) at some aggregation level (by detailed fuel type or by major fuel type) to total potential CO_2 in feedstock NEU fuels consumed

6: Sum of subcategories below including IPPU sources allocated to Fuel Combustion Activities 1A (due to transfer of by-product fuels to another source category (and 1B, 4C when appropriate))

7: Sum of subcategories of that category

TABLE 1.3 (UPDATED) (CONTINUED) VERIFICATION OF COMPLETENESS OF REPORTED CO_2 FROM NON-ENERGY USE OF FOSSIL FUELS

NOTES							Liquids												Gas	
1	Year:__________					Unit	Naphtha	Gas oil	Fuel Oil	Ethane	LPG b)	Petcoke	Other	Chem. gas	Lubricants	Waxes	Bitumen	Total liquids	Nat Gas	Total gas
2	A: Declared NEU (from commodity balance)					TJ												■		■
3	B: Carbon Content					kg C/GJ												■		■
	C: Total supplied for feedstock/non-energy	[C = A * B / 1000]				Gg C														
4	**D: Total supplied for feedstock/non-energy**	**[D = C * 44/12]**				Gg CO_2-eq.														
5	**E: Implied carbon fraction oxidised**	**[E = F / D * 100]**				%														
			Activity a)	CO_2 Emissions a)	IEF CO_2															
6	**F: Total fossil IPPU CO_2 reported**		■		■	Gg CO_2														
	2 INDUSTRIAL PROCESSES					Gg CO_2														
7	**2A: Mineral Industry**		■		■	Gg CO_2														
	(Please specify the subcategory.)					Gg CO_2														
7	**2B: Chemical Industry**		■		■	Gg CO_2														
	2B1: Ammonia Production					Gg CO_2													▣	
	2B5: Carbide Production					Gg CO_2						▣	□							
	2B6: Titanium Dioxide Production					Gg CO_2						□								
	2B8: Petrochemical and Carbon Black Production					Gg CO_2														
	2B8a: Methanol					Gg CO_2							□						▣	
	2B8b: Ethylene					Gg CO_2	▣	□	□	□	□									
	2B8f: Carbon Black					Gg CO_2							□						▣	
	2B10: Hydrogen					Gg CO_2	▣	□	□	□	▣		□						▣	
	2B11: Other					Gg CO_2														
7	**2C: Metal Industry**		■		■	Gg CO_2														
	2C1: Iron and Steel Production					Gg CO_2														
	2C2: Ferroalloys Production					Gg CO_2														
	2C3: Aluminium Production					Gg CO_2						□								
	2C5: Lead Production					Gg CO_2														
	2C6: Zinc Production					Gg CO_2														
	2C7: Rare Earths Production					Gg CO_2						□								
	2C8: Other					Gg CO_2														
7	**2D: Non-Energy Products from Fuels and Solvent Use**		■		■	Gg CO_2														
	2D1: Lubricant Use					Gg CO_2									▣					
	2D2: Paraffin Wax Use					Gg CO_2										▣				
	2D3: Solvent Use					Gg CO_2														
	2D4: Other					Gg CO_2							□				▣			
7	**2H: Other**		■		■	Gg CO_2														
	2H1: Pulp and Paper Industry					Gg CO_2														
	2H2: Food and Beverage Industry					Gg CO_2														
	2F3: Other					Gg CO_2							□							
	EXCEPTIONS REPORTED ELSEWHERE					Gg CO_2														
7	**1A FUEL COMBUSTION ACTIVITIES**		■		■	Gg CO_2														
	1A1a: Main Activity Electricity and Heat Production					Gg CO_2														
	1A1b: Petroleum Refining					Gg CO_2														
	1A1c: Manufacture of Solid Fuels and Other Energy Industries					Gg CO_2														
	1A2: Manufacturing Industries and Construction					Gg CO_2														

Note: In the tabular part, bolded boxes mark the main fuels as feedstock or reductant for the processes at the left hand side. Regular boxes mark other known feedstock/reductant for the processes at the left hand side.

1.4.3.2 FEEDSTOCK BALANCE CHECK

The principle of the *feedstock balance check* method is to compare the supply of feedstock/reductants as reported in national fuel statistics with the requirements for the feedstocks by each of the processes using them. A significant difference between the supply and the requirements of a feedstock leads to several suggested actions intended to identify omission of feedstock uses from the inventory or uses of fuel as feedstock that have been reported as fuel consumption or conversion.

Unlike the *CO_2 completeness check* the *feedstock balance check* is conducted at the level of fuel quantities and not CO_2 emissions. The method seeks confirmation that all feedstock carbon has been satisfactorily attributed to source categories identified in the inventory.

The workings of the method are explained below and readily set out in a worksheet (Table 1.5a). A list of feedstock fuels to be considered is presented in Table 1.4.

TABLE 1.4 (UPDATED)
LIST OF FUELS THAT CAN BE USED AS CHEMICAL FEEDSTOCK OR REDUCTANT

Solids	Liquids		Gases	Other fuels
coal	refinery gas	naphtha	natural gas	other fuel
metallurgical coke*	Ethane	kerosene		waste (fossil carbon)
petroleum coke*	propane	gas oil		Biofuels / biomass
coal tars and oils*	butane	fuel oil		
	LPG	waste oils		

* Includes uses as electrodes.

Step 1: Feedstock supply

Figures for supply of each feedstock/reductant are taken from national fuel statistics presented in commodity or energy balances. They will be shown as non-energy use or feedstock use according to the country’s particular conventions and reductants as inputs to a transformation process. The quantities should be expressed in, or converted to, Terajoules (TJ) using net calorific (lower heating) values (see Chapter 1 of Volume 2 for IPCC default values).

The definitional basis for feedstock reporting differs between countries and this consideration is fully discussed in Sections 1.2.1 and 1.3.2. Some care is therefore needed to identify and use the correct hydrocarbon input figures that will correspond with a process’s gross hydrocarbon requirements for the feedstock or reductant (including inputs not or only partly labelled as non-energy use in energy statistics). The total hydrocarbon process input attributed to feedstock/reductant use is required for the *feedstock balance check* described here, because the Specific Feedstock Consumption (SFC) figures of each process, as given in the table, include the fuel requirement. The SFC is the amount (expressed in TJ/Gg) of feedstock/reductant required per tonne of product produced.

Step 2: Feedstock requirements

The feedstock requirements of each process will include fuels taken directly or indirectly from the feedstock. Where the necessary data are available from industry sources they can then be entered into the ‘requirements’ part of the worksheet. Where the data are not available the requirements should be calculated from the production figures for the processes and where necessary, using expert judgement based on the emissions estimation used for the process(es). The figure for the process requirement is likely to be identical to the quantity supplied (taken from energy statistics) *only when* the latter has been obtained from industry sources.

When requirements are calculated from production using the spreadsheet the production figures are those relevant to the process for the given feedstock. If two or more feedstocks supply a single process then the corresponding production figures should be used for each feedstock.

Table 1.5b provides SFC factors linking production figures to feedstock requirements. The factors are the specific feedstock requirements of the process and include fuel use of the feedstock. The factors provided in Table 1.5b have been derived from the methods described in this volume of these *Guidelines* and may be considered as default values. It is *good practice* to use national factors if they are demonstrably more relevant than the default factors given here.

If R_{ij} represents the feedstock requirements of process i for feedstock j, then the total requirement for feedstock j (R_j), can be expressed as:

EQUATION 1.1
TOTAL FEEDSTOCK REQUIREMENT

$$R_j = \sum_i R_{ij} = \sum_i \left(SFC_{ij} \bullet P_{ij} \right)$$

Where:

R_j = total requirement for feedstock *j*, TJ

R_{ij} = feedstock requirements of process *i* for feedstock *j*, TJ

SFC_{ij} = Specific Feedstock Consumption of feedstock *j* in process *i*, TJ/Gg

P_{ij} = production from process *i* using feedstock *j*, Gg

The R_j is then compared with the figure for the supply of feedstock *j*. The difference appears in the Table 1.5a. The implementation procedure for this check is set out in the flowchart in Figure 1.3.

Step 3: Actions arising from the comparison

It is suggested that if the difference observed exceeds 10 percent of the feedstock supply action should be taken to check the data and, if the difference is confirmed, it should be investigated. The 10 percent threshold is necessarily arbitrary and chosen to reflect the likely overall inherent uncertainties in the data.

It is considered *good practice* to focus the investigation on differences in which feedstock supply significantly exceeds the apparent requirements because this suggests that:

- Processes and therefore sources of emissions may have been omitted; or
- The specific energy requirements used in the method are too low. The specific energy requirements should then be adjusted to reflect the national situation.

When the calculated requirements exceed the apparent feedstock supply it suggests that:

- Uses of feedstock fuels are reported elsewhere as fuel combustion or fuel conversion uses.
- A ‘net’ definition of feedstock supply may have been used in the energy statistics instead of a ‘gross’ definition (see the reference to ethylene and other chemicals in Section 1.3.2).
- Feedstock requirements, obtained directly from industry sources, are overstated through the inclusion of fuels entering the plant (or more generally, the source category) which are not used in the process and therefore not for feedstock use. The inclusion of non-feedstock fuels should not occur when the feedstock requirements are derived from production data.

Where significant discrepancies remain the likely causes of differences should be listed, taking into account the accuracy of the calculation with default Specific Feedstock Consumption values per source category/feedstock combination.

TABLE 1.5A (Updated) COMPARISON OF FEEDSTOCK SUPPLY WITH REQUIREMENTS IMPLIED BY PRODUCTION

YEAR		Feedstock or Reductant (TJ)	Process SFC (TJ/kt)	Production (Gg [=kt])
	Feedstock Quantity delivered			
	Difference			
Chemicals	Ammonia prodn		↑ Values from Table 1.5b ↓	
	Silicon carbide			
	Calcium carbide			
	Ethylene			
	Methanol			
	Carbon black			
	Hydrogen			
	Other			
Metals	Iron and steel			
	Ferroalloys			
	Aluminium			
	Zinc			
	Lead			
	Rare Earths			
	Other			

Table 1.5a is a reduced form of the full table in which the tabular part is replicated as many times as there are types of feedstock or reductant. In each of the replications the ‘Feedstock or Reductant’ heading in column 1 is replaced by the name of the fuel. The corresponding SFC values are then entered in column 2. The default SFC values are given in Table 1.5b below.

An Excel workbook is provided in the *2006 IPCC Guidelines* CDROM containing the full table, the default values and the formulae to carry out automatically the requirements calculation.

TABLE 1.5B (Updated) SPECIFIC FEEDSTOCK CONSUMPTION (TJ/Gg) FOR FEEDSTOCK/REDUCTANTS

		Coal	Met coke	Pet Coke	Coal tars and oils	Ref gas	Ethane	Propane	Butane	LPG	Naphtha	Kerosene	Gas oil	Fuel oil	Waste oils	Natural gas
Chemicals	Ammonia prodn													42(l)		37(o)
	Silicon carbide			36(e)												
	Calcium carbide			17(f)												
	Ethylene						59(j)	100(k)	104(k)	102(k)	137(k)					
	Methanol	72(a)												37(m)		34(p)
	Carbon black				60(h)									60(n)		12(q)
	Hydrogen prodn	215 (r)								165 (r)	165 (r)					165 (r)
	Other															
Metals	Iron and steel		14(b)													
	Ferroalloys															
	Aluminium			12(g)	3(i)											
	Zinc		21(c)													
	Lead		7(d)													
	Rare Earths			4 (s)	1 (s)											
	Other															

NOTES **(a) Methanol:** From Section 3.9.2.2; Table 3.13 Consult table for precise value according to process used.

(b) Iron and Steel: From Section 4.2.2.3:"Coke is consumed at a rate of about 475 kg/tonne of iron (or hot metal) produced." so coke requirement is 0.475 x cv(coke) 28.5 = 3.54 GJ/t iron.

(c) Zinc: From Section 4.7.1 (pyrometallurgical process only) taken from Sjardin(2003) Coke consumption is 0.74t coke/t zinc. That is: 0.74 x 28.5 GJ/t or 21 GJ coke / t zinc.

(d) Lead: taken from Sjardin(2003) Coke consumption is 0.26t coke/t lead. That is: 0.26 x 28.5 GJ/t or 7 GJ coke / t lead

(e) Silicon carbide: From Section 3.6.2.2: ". . . This implies a typical emission factor of 2.3 tonnes CO_2/tonne petroleum coke used (IPCC, 1996), or 2.62 tonnes CO_2/tonne carbide produced.

Or 2.62/2.3 t coke per t carbide; = 1.14 t coke/t carbide. That is; 1.14 x 32 = 36 GJ per tonne of SiC.

(f) Calcium carbide: From: Section 3.6.2.2 "1750 kg limestone (or 950 kg CaO), 640 kg of petroleum coke and 20 kg carbon electrodes are required to produce 1 tonne of carbide."
So coke requirement is:Prodn x (640-20) x CV(coke) per tonne of CaC_2. or .620 x 32.5 = 20.15 GJ/tonne CaC_2

(g) Aluminium: From Section 4.4.2.2; Table 4.11 average of two processes 1.65t CO_2/t alu. = 0.45tC/t alu. Assume anodes contain 84% coke and 16% pitch. (Sjardin 2003). Assume coke is 92% C and pitch 93% C. Assume CV calcined coke is 30MJ.kg and NCV for pitch 35.6MJ/kg. Then coke requirement is 12.3 GJ/t alu and pitch requirement 2.8 GJ/t alu.

(h) Carbon black: Assumed identical to fuel oil.

(i) Aluminium: See note for pet coke.

(j) Ethylene: From Section 3.9.2.3; Table 3.25 Ethane requirement is: NCV(Ethane)x1/yield matrix value. That is:47.5 x 1/0.803 = 59.15

(k) Ethylene: See ethane for sources and method.

(l) Ammonia: From 3.2.2.2; Table 3.1;Partial oxidation assumed

(m) Methanol: From Section 3.9.2.2; Table 3.13. Consult table for precise value according to process used.

(n) Carbon Black: Based on Voll et al and BREF LVIC Table 4.13

(o) Ammonia: From Section 3.2.2.2; Table 3.1

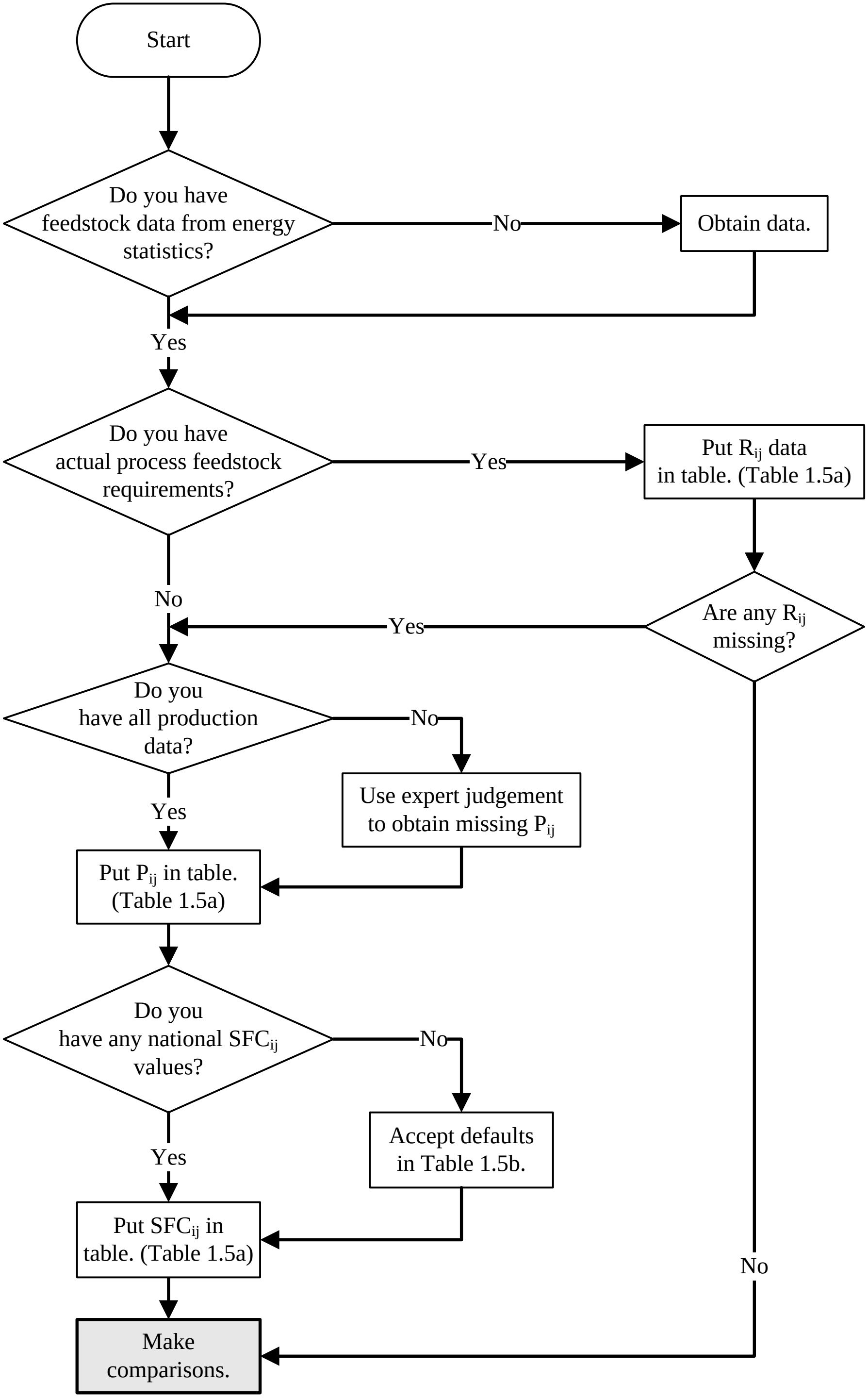
(p) Methanol: From Section 3.9.2.2; Table 3.13;Consult table for precise value according to process used.

(q) Carbon black: Based on Voll et al and BREF LVIC Table 4.13

(r) Hydrogen: From Section 3.11.2.2; Table 3.30 Consult table for precise value according to process used.

(s) Rare Earths: From Section 4.8.2.2; Table 4.26 indicates average emissions of 0.15 tC / t RE produced, which is one third that of Aluminium production.
Applying the same assumptions as for Aluminium in item (g) above derives the values for RE production for coke and pitch.

Figure 1.3 Flowchart for verification of completeness of accounting for non-energy uses of fuels



Note:
R_{ij} = feedstock requirements of process i for feedstock j, TJ
SFC_{ij} = Specific Feedstock Consumption of feedstock j in process i, TJ/Gg
P_{ij} = production from process i using feedstock j, Gg

1.4.4 Reporting and documentation of allocation and QC of completeness

It is *good practice* to review, summarise and document the completeness checks, if performed, for non-energy uses of fuels and fugitive emissions from fuel manufacture. This involves identifying the uses within the IPPU Sector, Fuel Combustion Activities (Category 1A) and Fuel Transformation activities (Category 1B) in the Energy Sector, as discussed in this section.

Different national methods exist for accounting for feedstock use of fuels in energy statistics and there is a possibility, in exceptional cases, of reporting part of the CO_2 in the Energy Sector (see Sections 1.2.1 and 1.3.2). Consequently, it is *good practice* to show in the inventory report:

- Where and how *non-energy* use of fuels has been accounted for in the inventory (whether in the Energy Sector or the Industrial Processes and Product Use Sector.) (Section 1.4.4.1).
- Where and how carbon emissions, other than CO_2, have been accounted for in the inventory. These arise from non-combustion and non-biogenic processes involving fossil carbon such as solvent use.
- Results of *completeness checks* performed, when applicable. Details on the QC activities on completeness should be kept as internal documentation (Section 1.4.4.2), in accordance with the guidance on QA/QC (see Chapter 6 of Volume 1).

The first bullet point refers to the allocation of corresponding emissions, in the IPPU Sector or, possibly, also in the Fuel Combustion Activities (Category 1A) in the Energy Sector, and to the definition of 'non-energy' or 'feedstock' used in the national energy statistics. Depending on the definition of the source categories, the contribution of feedstock and non-energy use CO_2 emissions varies from less than a percent up to about 5 percent of national total fossil fuel related CO_2 emissions.

The description of the completeness check should explain any allocation of a particular source to several sectors. In particular, how adjustments have been made to industrial process emissions should be explained in cases where fuel by-products (off-gases or process vent gas) are transferred to another source category in the IPPU Sector or in the Energy Sector.

1.4.4.1 ALLOCATION OF CO_2 FROM NON-ENERGY USE

Table 1.6 can be used to document and report the following information, summarising the subcategories in which the sectoral CO_2 emissions (other than those from fuel combustion) from the fossil fuels used are reported. The amounts of each fuel type consumed for non-combustion purposes (which correspond to excluded carbon in the CO_2 Reference Approach) should be recorded as internal documentation. This relates to:

- The division between *manufacturing process emissions* reported in the IPPU Sector and *fuel combustion emissions* reported in the Energy Sector.
- The allocation of CO_2 emissions from the *direct use* of 'fuels' for their physical properties and from the *use* of chemical products in the IPPU Sector. The emissions from the *waste disposal* of these products (e.g., incineration) are dealt with in the Waste Sector.

In the allocation reporting table (Table1.6) the 'Primary NEU fuel type' and 'Other NEU fuel types' should be entered for each category. The same CO_2 emissions reported in the IPPU sectoral background table are entered into the IPPU emissions column (or the notation keys NE, NO, IE, where applicable). Then CO_2 emissions related to the use of fossil fuels for non-energy purposes reported in source categories other than IPPU are added to the appropriate 1A subcategories. These are labelled in the IPPU source categories as (partly) included elsewhere in the IPPU reporting with a reference to where they are reported. Thus the table includes all emissions from the IPPU Sector wherever they are reported and so documents the complete reporting of these emissions in the IPPU and Energy Sectors.

The inclusion of the Energy Sector improves transparency of complete CO_2 emissions reporting as regards the emissions from waste gases and other gases such as blast furnace gas produced from industrial processes but used for fuel combustion in other economic sectors and thus reported in the Energy Sector.

1.4.4.2 COMPLETENESS OF CO_2 FROM NON-ENERGY USE

In addition to the summary of the review of the allocation and completeness of emissions from non-energy uses of fossil fuels it is *good practice* to document:

- A description of the emission calculation methods used, in the respective source category sections of the report. This should include the reason for any departure of allocations compared to the suggested IPCC source classification, if applicable.
- The results of the *CO_2 completeness check* if used, for at least the base year (where data permit) and the last reported year, presented in a table such as Table 1.3, as internal documentation.
- If the *feedstock balance check* for completeness was also used, a table showing the difference between the inferred estimate of feedstock consumption and the reported feedstock deliveries; at minimum for the base year (where data permit) and the two most recent years (i.e., as in Table 1.5a) as internal documentation.
- An explanation of significant unexpected discrepancies, if any, in level or trend. This should include the main cause of these differences.
- Conclusions from the comparison in terms of whether significant CO_2 emissions seem to be missing, and if so, in which part of the inventory they occur, and an estimate of the sizes of the omissions.
- A summary of bio-CO_2 emissions from the use of bio-fuels and biomass feedstocks that are reported as memo items to the national inventory.

Table 1.6 (Updated)
Allocation of CO_2 from non-energy use of fossils fuels: IPPU and other Sectors

Category	Reported in year: ……..				Notes
	Primary NEU fuel (1)	Other NEU fuel(s) (1)	Emissions Amount Reported in IPPU Sector CO_2 (2) (Gg)	In case reported elsewhere: Sub-category in 1A where these emissions are (partly) reported	
2 Industrial Processes and Product Use					
2A Mineral Industry					
(Please specify the sub-category)	(coal, ..)				4
2B Chemical Industry					
2B1 Ammonia Production	natural gas	oil, coal			
2B5 Carbide Production	pet coke	oil			
2B6 Titanium Dioxide Production	coal				
2B8 Petrochemical and Carbon Black Production					
2B8a Methanol	natural gas	coal, oil			5
2B8b Ethylene	naphtha	gas oil; butane, ethane, propane, LPG			5
2B8f Carbon Black	natural gas	oil, coke oven gas			
2B10 Hydrogen	natural gas	LPG, naphtha, coal, methanol			6
2B11 Other					
2C Metal Industry					
2C1 Iron and Steel Production	coke	coal, pet coke (carbon electrode)			7
2C2 Ferroalloys Production	(carbon electrode)	coke, coal			8
2C3 Aluminium Production	(carbon electrode)	coke, coal			8
2C5 Lead Production	coke				
2C6 Zinc Production	coke				
2C7 Rare Earths Production	(carbon electrode)	coke, coal			8
2C8 Other	(carbon electrode)	coke, coal			
2D Non-Energy Products from Fuels and Solvent Use					
2D1 Lubricant Use	lubricants	greases			
2D2 Paraffin Wax Use	waxes				
2D3 Solvent Use	(mineral turpentine)	coal tars and oils			9
2D4 Other					10
2H Other					
2H1 Pulp and Paper Industry					
2H2 Food and Beverages Industry	coke				
2H3 Other					
1 ENERGY					
1A Fuel Combustion Activities			**Reported in Sector 1A (3)**		
1A1a Main Activity Electricity and Heat Production	(BF gas)	(chemical off-gases)			11
1A1b Petroleum Refining					
1A1c Manufacture of Solid Fuels and Other Energy Industries	BF gas				
1A2 Manufacturing Industries and Construction	(BF gas)	(lubricants, chemical off-gases))			

(1) The columns ‘Primary NEU fuel’ and ‘Other NEU fuel’ should be completed with the actual fuel types used.

(2) These are the same emissions reported in the sectoral background table (also the same emissions notation keys NE, NO, IE, where applicable). If (partly) reported elsewhere, a reference to that other source category should be added in the next column.

(3) Report here only the CO_2 emissions from combustion of waste gases produced from industrial processes but used for fuel combustion in other economic sectors and reported in the Energy sector.(e.g. from combustion of blast furnace gas or chemical off-gases transferred offsite to another source category).

(4) For example powdered anthracite coal may be used in Glass Production (2A3).

(5) In cases where the production of off-gases (i.e. byproduct gases) is fully accounted for in the energy statistics, the combustion of these gases may be used to calculate and report CO_2 emissions from the feedstock losses. Part of these off-gases may be combusted off-site (i.e. in a sector other than the petrochemical industry) and should thus be accounted for separately as fuel combustion in the Energy Sector.

(6) In some cases the emissions from feedstock use to produce hydrogen will be accounted for within other source categories, including petroleum refining (1A1b) and ammonia production (2B1).

(7) Part of the blast furnace gas produced from coke used in blast furnaces may be combusted off-site (i.e. in a sector other than the iron and steel industry) and should thus be accounted for separately as fuel combustion in the Energy Sector.

(8) Carbon electrodes are generally manufactured from coke, coal or tar either on-site by the users themselves or separately by anode production plants and then sold to users domestically and/or exported. If anodes are also imported and/or exported, there is no direct correspondence between fuels used for anode production and the amounts of anodes used in the country.

(9) Mineral turpentines are often used as solvent, possibly blended with other liquids. Aromatics derived from coal oils may also be used as solvents.

(10) Emissions from asphalt production, paving of roads and roofing should be reported under 2D4. However, bitumen - and other oil as diluent or 'road oil' - used for this activity does not result in CO_2 emissions.

(11) CO_2 from blast furnace gas and chemical off-gases should be reported here only when utilised in public power or heat production.

1.5 CHOOSING BETWEEN THE MASS-BALANCE AND EMISSION-FACTOR APPROACHES

No refinement.

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CHAPTER 3

CHEMICAL INDUSTRY EMISSIONS

Authors

Sections 3.3

Retno Gumilang Dewi (Indonesia) and María José López Blanco (Spain)

Sections 3.10

Karen S. Schaffner (USA), Deborah A. Ottinger (USA) and Brian T. Mader (USA)

Sections 3.11

Håkon Frøysa Skullerud (Norway), Katsuhiko Hirose (Japan) and Samir Tantawi (Egypt)

Contributing Authors

Sections 3.10

Jeffrey B. Coburn (USA) and Gregory M. Watson (USA)

Sections 3.11

Richard Chahine (Canada), Shohei Oyama (Japan) and Nigel Brandon (UK)

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3 CHEMICAL INDUSTRY EMISSIONS

Users are expected to go to Mapping Tables in Annex 5, before reading this chapter. This is required to correctly understand both the refinements made and how the elements in this chapter relate to the corresponding chapter in the 2006 IPCC Guidelines.

3.1 INTRODUCTION

No refinement.

3.2 AMMONIA PRODUCTION

No refinement.

3.3 NITRIC ACID PRODUCTION

3.3.1 Introduction

No refinement.

3.3.2 Methodological issues

Introduction – No refinement.

3.3.2.1 CHOICE OF METHOD

No refinement.

3.3.2.2 CHOICE OF EMISSION FACTORS

TIER 1 METHOD

It is *good practice* to use the highest emission factor based on the technology type shown in Table 3.3 and to assume that there is no abatement of nitrous oxide (N_2O) emissions.

TIER 2 METHOD

If plant-level factors are not available, it is *good practice* to use default factors. These default values often represent midpoint or mean values of data sets (as determined by expert analysis). The extent to which they represent a specific plant's emission rate is unknown. Default factors in Table 3.3 should be used only in cases where plant-specific measurements are not available.

Table 3.3 includes emission factors for N_2O, and associated uncertainties by type of production process.

The five production process types are distinguished according to the pressures applied in the oxidation and absorption stage as presented in Table 3.3a (new).

TABLE 3.3A (NEW)
DIFFERENT PLANT TYPES FOR THE PRODUCTION OF HNO_3[1]

Type	Operation Condition	Applied Pressure in Bar	
		Oxidation	Absorption
L/L	Single Low Pressure	0 - 1.7	
L/M	Dual Low/Medium Pressure	<1.7	1.7 – 6.5
M/M	Single Medium Pressure	1.7 - 6.5	
M/H	Dual Medium/High Pressure	1.7 – 6.5	6.5 - 13
H/H	Single High Pressure	6.5 - 13	

Source:

[1] EC, 2007 (with reference of EFMA, 2000 and Schöffel, 2001)

The factors listed in Table 3.3 for plants using abatement technology, incorporate the effect of N_2O abatement measures. To use these factors, inventory compilers should verify that the abatement technology is installed at individual plants and operated throughout the year.

TABLE 3.3 (UPDATED)
DEFAULT FACTORS FOR NITRIC ACID PRODUCTION

Production Process	N_2O Emission Factor (relating to 100 percent pure acid)
Old (pre-1975) plants* (all processes)	10-19 kg N_2O/tonne nitric acid[a]
Single low pressure plants	5 kg N_2O/tonne nitric acid ±10%
Single medium pressure plants	8 kg N_2O/tonne nitric acid ±20%[b]
Single high pressure plants	9 kg N_2O/tonne nitric acid ±40%
Single pressure plants with abatement technology**	2.5 kg N_2O/tonne nitric acid ±10%[b]
Dual Pressure (M/H)	9 kg N_2O/tonne nitric acid ±30%[b]
Dual Pressure (M/H) with abatement technology	2.5 kg N_2O/tonne nitric acid ±20%[b]
Dual Pressure (L/M)	7 kg N_2O/tonne nitric acid ±20%[b]
Dual Pressure (L/M) with abatement technology	1.5 kg N_2O/tonne nitric acid ±10%[b]

Notes:

* Old (pre-1975) plants means that the EF is to be used for the technology that was installed before 1975 and that are still operating.

** Applies to all single pressure plants using all levels of N_2O abatement measures (primary, secondary, tertiary and quaternary). These abatement measures include all levels of abatement such as process-integrated abatement technologies, tailgas N_2O destruction and non-selective catalytic reduction (NSCR, a NOx abatement technology that can also be managed to abate N_2O).

Source:

[a] Based on IPCC, 2000; EC, 2007; and the tests from Clean Development Mechanism (CDM) projects presented in US EPA, 2010.

[b] Based on information from EC, 2007; EC, 2009; 2017 Annex I Party GHG Inventory Submissions; Joint Implementation projects and Clean Development Mechanism projects availables at the UNFCCC web-site.

TIER 3 METHOD

Plant measurements provide the most rigorous data for calculating net emissions (i.e., N_2O generation and destruction factors). Monitoring N_2O emissions from nitric acid production is practical because these are point sources and there are a finite number of production plants. Given currently available technology, instrumentation for sampling and monitoring emission rates do not limit precision or accuracy of the overall measurement. Usually sampling frequency and timing is sufficient to avoid systematic errors and to achieve the desired level of accuracy.

As a general rule, it is *good practice* to conduct sampling and analysis whenever a plant makes any significant process changes that would affect the generation rate of N_2O, and sufficiently often otherwise to ensure that operating conditions are constant. In addition, plant operators should be consulted annually to determine the specific destruction technologies employed and confirm their use, since technologies may change over time. Precise measurement of the emissions rate and abatement efficiencies requires measurement of both the exit stream and the uncontrolled stream. Where measurement data are available only on the exit stream, *good practice* is to base emissions on these data. In this case, any available estimates of abatement efficiency should be provided only for information purposes and are not used to calculate emissions.

3.3.2.3 CHOICE OF ACTIVITY DATA

No refinement.

3.3.2.4 COMPLETENESS

No refinement.

3.3.2.5 DEVELOPING A CONSISTENT TIME SERIES

No refinement.

3.3.3 Uncertainty assessment

No refinement.

3.3.4 Quality Assurance/Quality Control (QA/QC), Reporting and Documentation

No refinement.

3.4 ADIPIC ACID PRODUCTION

No refinement.

3.5 CAPROLACTAM, GLYOXAL AND GLYOXYLIC ACID PRODUCTION

No refinement.

3.6 CARBIDE PRODUCTION

No refinement.

3.7 TITANIUM DIOXIDE PRODUCTION

No refinement.

3.8 SODA ASH PRODUCTION

No refinement.

3.9 PETROCHEMICAL AND CARBON BLACK PRODUCTION

No refinement.

3.10 FLUOROCHEMICAL PRODUCTION

3.10.1 HFC-23 emission from HCFC-22 production

3.10.1.1 INTRODUCTION

No refinement.

3.10.1.2 METHODOLOGICAL ISSUES

CHOICE OF METHOD

There are two broad measurement approaches to estimating HFC-23 emissions from HCFC-22 plants. These are described in IPCC (2000), DEFRA (2002a and 2002b), EFCTC (2003) and UN (2004) and have been translated into Tier 2 and 3 methodologies described below. National emissions using either of these methodologies are the sum of those from the individual facilities. Tier 1 (default) methodology can be applied to individual plants or, if there is no abatement by destruction, to the total national output of HCFC-22. Accounting for HFC-23 emissions is not simply mechanistic but requires information on the process operations responsible for producing and emitting HFC-23, so that the most appropriate methodology and factors can be adopted. Therefore, it is *good practice*, to the extent possible, to establish contacts with plant managers in order to obtain the necessary data.

The Tier 1 method is relatively simple, involving the application of a default emission factor to the quantity of HCFC-22 produced. This method can be applied at the plant level or the national level. Tier 2 and Tier 3 methodologies are suitable only for plant level calculations because they rely on data that are only available from plants. In cases where there are Tier 3 data available for some plants, the Tier 1 or Tier 2 methods can be applied to the remainder to ensure complete coverage.

It is *good practice* to estimate national emissions by summing measured parameters from all HCFC-22 plants in a country. Tier 3 plant emission measurements are the most accurate, followed by Tier 2 measurements based on plant efficiencies. Direct measurement is significantly more accurate than Tier 1 because it reflects the conditions specific to each manufacturing facility. In most cases, the data necessary to prepare Tier 3 estimates should be available because facilities operating to good business practice perform regular or periodic sampling of the final process vent or within the process itself as part of routine operations. The Tier 1 (default) method should be used only in cases where plant-specific data are unavailable and this subcategory is not identified as significant subcategory under *key category*. (See Section 4.2 of Volume 1.) Modern plant using process optimization will need to keep accurate HFC-23 generation data as part of this optimization, so plant-specific data should be available to most countries in most cases.

The choice of *good practice* method will depend on national circumstances. The decision tree in Figure 3.16 describes *good practice* in adapting the methods in these Guidelines to country-specific circumstances.

Procedures to abate emissions include destruction of HFC-23 in a discrete facility and, in this case, emissions occur only when the destruction facility is not in operation. The tiers of methodology provide estimates for the quantity of HFC-23 that is produced and the share of production that is ultimately emitted depends on the length of time that the destruction facility is not operated. For facilities using abatement techniques such as HFC-23 destruction, verification of the abatement efficiency is also done routinely. It is *good practice* to subtract abated HFC-23 emissions from national estimates where the abatement has been verified by process records on every plant.

Tier 1

In the Tier 1 methodology, a default factor is used to estimate production (and potential emissions) of HFC-23 from the total HCFC-22 production from each facility (for both potentially dispersive uses, as reported under the Montreal Protocol, and feedstock uses, which are reported separately to the Ozone Secretariat). See Equation 3.30.

EQUATION 3.30
TIER 1 CALCULATION OF HFC-23 FROM HCFC-22 (PRODUCED) USING DEFAULT FACTOR

$$E_{HFC-23} = EF_{default} \bullet P_{HCFC-22}$$

Where:

E_{HFC-23} = by-product HFC-23 emissions from HCFC-22 production, kg

$EF_{default}$ = HFC-23 default emission factor, kg HFC-23/kg HCFC-22

$P_{HCFC-22}$ = total HCFC-22 production, kg

This methodology is suitable where plant-specific measurements are not available and, in that case, the default condition is that all of the estimated HFC-23 production is released into the atmosphere.

Tier 2

In the Tier 2 methodology, the HFC-23 emission factor is derived from records of process efficiencies and used in the calculation shown as Equation 3.31. This is a material balance approach and relies on calculating the difference between the expected production of HCFC-22 and the actual production and then assigning that difference to loss of raw materials, loss of product (HCFC-22) and conversion to by-products, including HFC-23. These parameters will be different for each plant and so should be assessed separately for each facility reporting into the national data.

EQUATION 3.31
TIER 2 CALCULATION OF HFC-23 FROM HCFC-22 (PRODUCED) USING FACTOR(S) CALCULATED FROM PROCESS EFFICIENCIES

$$E_{HFC-23} = EF_{calculated} \bullet P_{HCFC-22} \bullet F_{released}$$

Where:

E_{HFC-23} = by-product HFC-23 emissions from HCFC-22 production, kg

$EF_{calculated}$ = HFC-23 calculated emission factor, kg HFC-23/kg HCFC-22

$P_{HCFC-22}$ = total HCFC-22 production, kg

$F_{released}$ = Fraction of the year that this stream was released to atmosphere untreated, fraction

The emission factor can be calculated from both the carbon efficiency (Equation 3.32) and the fluorine efficiency (Equation 3.33) and the value used in Equation 3.31 should normally be the average of these two values unless there are overriding considerations (such as a much lower uncertainty of one of the efficiency measures) that can be adequately documented. Annual average carbon and fluorine balance efficiencies are features of a well-managed HCFC-22 plant and are either normally available to the plant operator or may be obtained by examination of process accounting records. Similarly, if there is a vent treatment system, the length of time that this was in operation, and treating the vent stream from the HCFC-22 plant, should be available from records.

Total HCFC-22 production includes material that is used as a chemical feedstock as well as that which is sold for potentially dispersive uses.

EQUATION 3.32
CALCULATION OF HFC-23 EMISSION FACTOR FROM CARBON BALANCE EFFICIENCY

$$EF_{carbon\_balance} = \frac{(100 - CBE)}{100} \bullet F_{efficiency\ loss} \bullet FCC$$

Where:

$EF_{carbon\_balance}$ = HFC-23 emission factor calculated from carbon balance efficiency, kg HFC-23/kg HCFC-22

CBE = carbon balance efficiency, percent

$F_{efficiency\ loss}$ = factor to assign efficiency loss to HFC-23, fraction

FCC = factor for the carbon content of this component (= 0.81), kg HFC-23/kg HCFC-22

and

EQUATION 3.33
CALCULATION OF HFC-23 EMISSION FACTOR FROM FLUORINE BALANCE EFFICIENCY

$$EF_{fluorine\_balance} = \frac{(100 - FBE)}{100} \bullet F_{efficiency\ loss} \bullet FFC$$

Where:

$EF_{fluorine\_balance}$ = HFC-23 emission factor calculated from fluorine balance efficiency, kg HFC-23/kg HCFC-22

FBE = fluorine balance efficiency, percent

$F_{efficiency\ loss}$ = factor to assign efficiency loss to HFC-23, fraction

FFC = factor for the fluorine content of this component (= 0.54), kg HFC-23/kg HCFC-22

The factor to assign the efficiency loss to HFC-23 is specific to each plant and, if this method of calculation is used, the factor should have been established by the process operator. By default, the value is 1; that is all of the loss in efficiency is due to co-production of HFC-23. In practice, this is commonly the most significant efficiency loss, being much larger than losses of raw materials or products.

The factors for carbon and fluorine contents are calculated from the molecular compositions of HFC-23 and HCFC-22 and are common to all HCFC-22 plants at 0.81 for carbon and 0.54 for fluorine.

Tier 3

Tier 3 methodologies are potentially the most accurate. The Tier 3 methodologies provided here give equivalent results and the choice between them will be dictated by the information available in individual facilities. In each case, the national emission is the sum of factory specific emissions, each of which may be determined using a Tier 3 method to estimate the composition and flowrate of gas streams vented to atmosphere (either directly and continuously – as in Tier 3a - or by continuous monitoring of a process parameter related to the emission - Tier 3b - or by monitoring the HFC-23 concentration continuously within the reactor product stream - Tier 3c):

EQUATION 3.34
TIER 3A CALCULATION OF HFC-23 EMISSIONS FROM INDIVIDUAL PROCESS STREAMS (DIRECT METHOD)

$$E_{HFC-23} = \sum_i \sum_j \int_t C_{ij} \bullet f_{ij} \quad [\textstyle\int_t \text{ means the quantity should be summed over time.}]$$

Where:

E_{HFC-23} = total HFC-23 emissions: the sum over all *i* plants, over all *j* streams in each plant of the emitted mass flows *f* and concentrations *C* is integrated over time *t*. (See Equation 3.37 for calculation of 'instantaneous' HFC-23 emissions in an individual process stream.)

or, where an emission factor-based methodology is used:

EQUATION 3.35 (UPDATED)
TIER 3B CALCULATION OF HFC-23 EMISSIONS FROM INDIVIDUAL PROCESS STREAMS USING A SITE- OR PROCESS-SPECIFIC EMISSION FACTOR

$$E_{HFC-23} = \sum_i \int_t C_i \bullet P_i \quad [\textstyle\int_t \text{ means the quantity should be summed over time.}]$$

Where:

E_{HFC-23} = total HFC-23 emissions: $E_{i,j}$ are the emissions from each plant and stream determined using an emission factor. (See Equation 3.38 for calculation of HFC-23 emissions in an individual process stream.)

or, where the HFC-23 concentration within the reactor product stream is used:

EQUATION 3.36
TIER 3C CALCULATION OF HFC-23 EMISSIONS FROM INDIVIDUAL PROCESS STREAMS (BY MONITORING REACTOR PRODUCT)

$$E_{HFC-23} = \sum_{i} \int_{t} C_i \bullet P_i \quad [\int_t \text{ means the quantity should be summed over time.}]$$

Where:

E_{HFC-23} = total HFC-23 emissions: P_i is the mass flow of HCFC-22 product from the plant reactor at the plant i, and C_i is the concentration of HFC-23 relative to the HCFC-22 product at the plant i. (See Equation 3.40 for calculation of HFC-23 emissions at an individual facility by in-process measurement.)

Tier 3a

The Tier 3a method is based on frequent or continuous measurement of the concentration and flow-rate from the vent at an individual plant. So that the quantity emitted to atmosphere is the mathematical product of the mass concentration of the component in the stream, the flowrate of the total stream (in units compatible with the mass concentration) and the length of time that this flow occurred:

EQUATION 3.37
TIER 3A CALCULATION OF 'INSTANTANEOUS' HFC-23 EMISSIONS IN AN INDIVIDUAL PROCESS STREAM (DIRECT METHOD)

$$E_{ij} = C_{ij} \bullet f_{ij} \bullet t$$

Where:

E_{ij} = 'instantaneous' HFC-23 emissions from process stream *j* at plant *i*, kg

C_{ij} = the concentration of HFC-23 in the gas stream actually vented from process stream *j* at plant *i*, kg HFC-23/kg gas

f_{ij} = the mass flow of the gas stream from process stream *j* at plant *i* (generally measured volumetrically and converted into mass flow using standard process engineering methods), kg gas/hour

t = the length of time over which these parameters are measured and remain constant, hours

If any HFC-23 is recovered from the vent stream for use as chemical feedstock, and hence destroyed, it should be discounted from this emission; material recovered for uses where it may be emitted may be discounted here, if the emissions are included in the quantity calculated by the methods in Chapter 7. Because emissions are measured directly in this tier, it is not necessary to have a separate term for material recovered, unlike Tiers 3b and 3c.

The total quantity of HFC-23 released is then the annual sum of these measured instantaneous releases. Periods when the vent stream is processed in a destruction unit to remove HFC-23 should not be counted in this calculation. If it is necessary to estimate the quantity destroyed at each facility, the operator should calculate this based on the difference between the operating time of the plant and the duration of release (*t* above).

Tier 3b

In many cases, measurements are not continuous but were gained during an intensive process survey or plant trial, and the results of the trial may be used to provide an emission factor for calculating emissions during normal plant operation. In this case, the emission rate of the by-product is related to a more easily (or accurately) measurable parameter, such as feedstock flow rate. The trial(s) must meet the following conditions:

- There should have been no major process design, construction or operating changes that affect the plant upstream of the measurement point and so could render relationships between emissions and production invalid. (See also Box 3.14)
- The relationship between emissions and plant operating rate must be established during the trial(s), together with its uncertainty.

For almost all cases the rate of plant operation is a suitable process operating parameter and the quantity of HFC-23 emitted depends on the current plant operating rate and the length of time that the vent flow was released.

EQUATION 3.38 (UPDATED)
TIER 3B CALCULATION OF HFC-23 EMISSIONS IN AN INDIVIDUAL PROCESS STREAM USING A SITE- OR PROCESS-SPECIFIC EMISSION FACTOR

$$E_{ij} = S_{ij} \bullet F_{ij} \bullet POR_{ij} \bullet t - R_{ij}$$

Where:

E_{ij} = the mass emission of HFC-23 in vent stream *j* at plant *i*, kg

S_{ij} = the standard mass emission factor of HFC-23 in vent stream *j* at plant *i* per 'unit' of a process operating parameter, such as process operating rate (described in Equation 3.39, below), kg/'unit'

F_{ij} = a dimensionless factor relating the measured standard mass emission rate to the emission rate at the actual plant operating rate. In many cases, the fraction produced is not sensitive to operating rate and F_i is unity (i.e., the emission rate is proportional to operating rate). In other cases the emission rate is a more complex function of the operating rate. In all cases F_i should be derived during the plant trial by measuring HFC-23 production at different operating rates. For situations where a simple function relating the emissions to the operating rate cannot be determined from testing, the emission factor-based method is not considered appropriate and continuous measurement is desirable.

POR_{ij} = the current process operating rate applicable to vent stream *j* at plant *i* averaged over *t* in 'unit/hour'. The units of this parameter must be consistent between the plant trial establishing the standard emission rate and the estimate of ongoing, operational emissions (described in Equation 3.39, below).

t = the actual total duration *of venting* for the year, or the period if the process is not operated continuously in hours. Annual emissions become the sum of all the periods during the year. The periods during which the vent stream is processed in a destruction system should not be counted here.

R_{ij} = the quantity of HFC-23 recovered for vent stream *j* at plant *i* for use as chemical feedstock, and hence destroyed, kg. Material recovered for uses where it may be emitted potentially may be counted here if the emissions are included in the quantity calculated by the methods for ODS substitutes in Chapter 7 of this volume.

EQUATION 3.39 (UPDATED)
TIER 3B CALCULATION OF STANDARD EMISSION FOR EMISSION FACTOR-BASED METHOD

$$S_{T,ij} = C_{T,ij} \bullet f_{T,ij} \, / \, POR_{T,ij}$$

Where (for each test T):

S_{ij} = the standard mass emission factor of HFC-23 in vent stream j at plant i, kg/'unit' (in units compatible with the factors in Equation 3.38, see $POR_{T,ij}$ below)

$C_{T,ij}$ = the average mass fractional concentration of HFC-23 in vent stream j at plant i during the trial, kg/kg

$f_{T,ij}$ = the average mass flowrate of vent stream j at plant i during the trial, kg/hour

$POR_{T,ij}$ = the process operating parameter (such as process operating rate) at plant i during the trial, 'unit'/hour. The 'unit' depends on the process operating parameter chosen to be representative for plant i vent stream j (for example, kg/hour or m^3/hour of feedstock)

Tier 3c

It is a relatively simple procedure to monitor the concentration of HFC-23 in the product of a reaction system relative to the amount of HCFC-22. This provides a basis for estimation of the quantity of HFC-23 released as the mathematical product of the monitored concentration and the mass flow of HCFC-22 made. If there is no vent treatment to abate emissions, this is a simple procedure. However, where there is abatement then it must be shown that this actually treats all streams that may be released into the atmosphere, including direct gas vents and the outgassing of aqueous streams. The latter, especially, may not be passed to the destruction facility. If all potential vent streams are not treated, the method cannot be used.

EQUATION 3.40

TIER 3C CALCULATION OF HFC-23 EMISSIONS FROM AN INDIVIDUAL FACILITY BY IN-PROCESS MEASUREMENT

$$E_i = C_i \bullet P_j \bullet t_F - R_i$$

Where:

E_i = HFC-23 emissions from an individual facility i, kg

C_i = the concentration of HFC-23 in the reactor product at facility i, kg HFC-23/kg HCFC-22

P_i = the mass of HCFC-22 produced at facility i while this concentration applied, kg

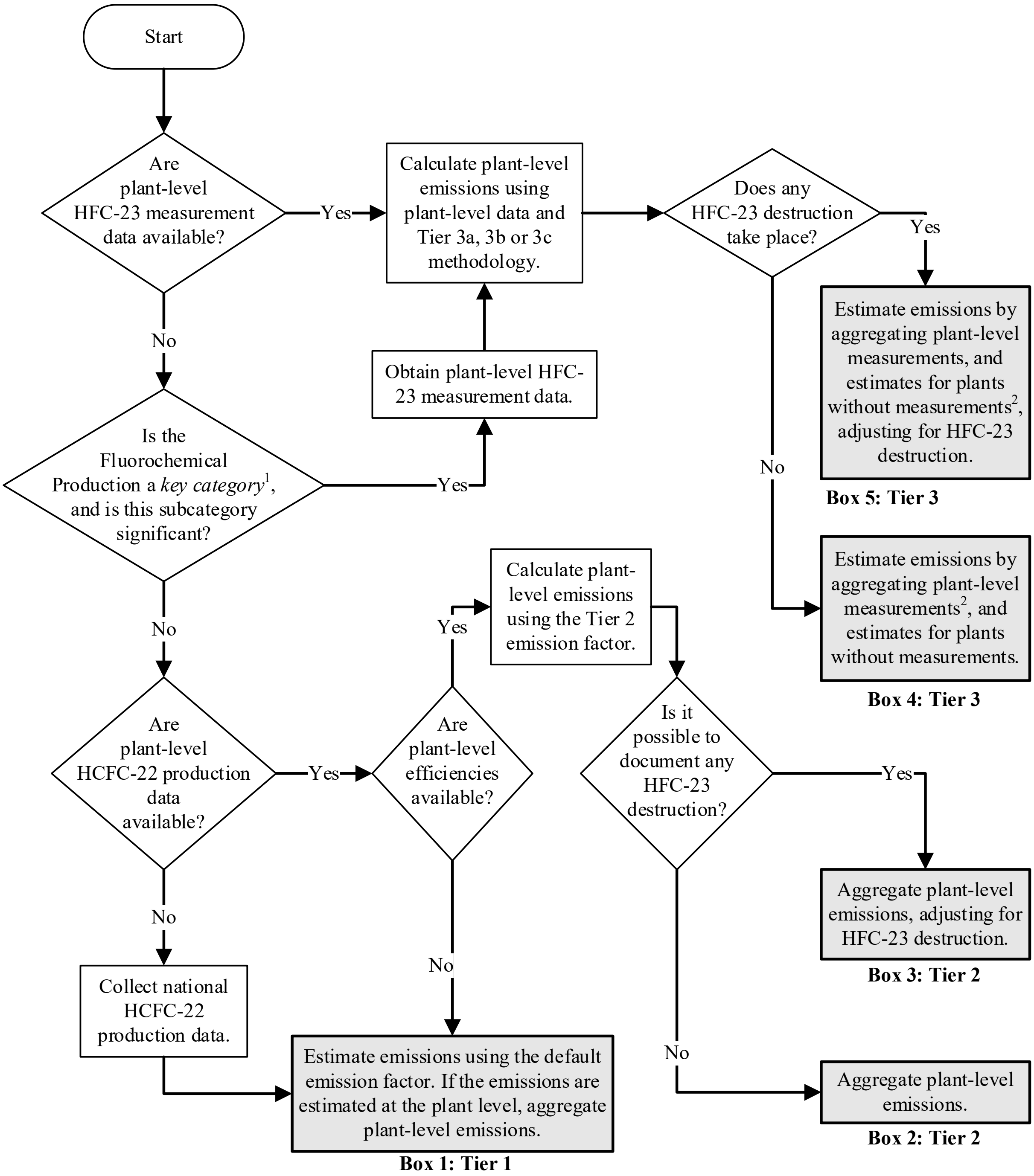
t_F = the fractional duration during which this HFC-23 is actually vented to the atmosphere, rather than destroyed, fraction

R_i = the quantity of HFC-23 recovered from facility i for use as chemical feedstock, and hence destroyed, kg. Material recovered for uses where it may be emitted potentially may be counted here if the emissions are included in the quantity calculated by the methods in Chapter 7 of this volume.

The total quantity of HFC-23 released into the atmosphere is the sum of the quantities from the individual release periods and individual reaction systems. HFC-23 that is recovered for use as chemical feedstock should be subtracted from the total quantity estimated here.

In summary, the Tier 1 method is relatively simple, involving the application of a default emission factor to the quantity of HCFC-22 produced. This method can be applied at the plant level or the national level. Tier 2 and Tier 3 methodologies are suitable only for plant level calculations. In cases where there are Tier 3 data available for some plants, the Tier 1 or Tier 2 methods can be applied to the remainder to ensure complete coverage. Uncertainty in the national emission is then calculated using production weighted uncertainties of the individual sources and standard statistical techniques. Regardless of the method, emissions abated should be subtracted from the gross estimate from each plant to determine net emissions before these are added together in the national estimate.

Figure 3.16 Decision tree for HFC-23 emissions from HCFC-22 production (or other similar by-product emissions from fluorochemical production)



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.
2. If there are Tier 3 data available for some plants, the Tier 1 or Tier 2 methods can be applied to the remainder to ensure complete coverage.

It is *good practice* to use the Tier 3 method if possible. Direct measurement is significantly more accurate than Tier 1 because it reflects the conditions specific to each manufacturing facility. In most cases, the data necessary to prepare Tier 3 estimates should be available because facilities operating to good business practice perform regular or periodic sampling of the final process vent or within the process itself as part of routine operations. For facilities using abatement techniques such as HFC-23 destruction, verification of the abatement efficiency is also done routinely. The Tier 1 (default) method should be used only in rare cases where plant-specific data are unavailable and this subcategory is not identified as significant subcategory under *key category*. (See Section 4.2 of Volume 1.)

CHOICE OF EMISSION FACTORS

There are several measurement options within the Tier 3 method relating to the location and frequency of the sampling. In general, direct measurement of the emissions of HFC-23 may provide the highest accuracy but continuous or frequent measurement of parameters within the production process area itself may be more pragmatic and can be equally accurate. In both cases, the frequency of measurement must be high enough to represent the variability in the process (e.g., across the life of the catalyst). Issues related to measurement frequency are summarised in Box 3.14, Plant Measurement Frequency. General advice on sampling and representativeness is provided in Volume 1, Chapter 2.

In cases where plant-specific measurements or sampling are not available and Tier 1 methods are used, the default emission factor should be used, assuming no abatement methods. For plants in operation prior to 1995 the default emission factor is 0.04 kg HFC-23/kg HCFC-22 (4 percent) (IPCC, 1996; US EPA, 2001; McCulloch, 2007). This is a default to be used when there are no measurements and describes the output of HFC-23 from a typical HCFC-22 plant in the absence of recovery or destruction of HFC-23. The value is consistent with atmospheric observations of HFC-23 concentrations in the 1978-1995 time period (Oram *et al.,*1998). These showed globally averaged emissions to be equivalent to 2 percent of the total quantity of HCFC-22 produced at a time when significant HFC-23 was being recovered and converted into Halon 1301 (McCulloch, 1992) and abatement was required practice in several countries where there was significant production.

It is possible, by process optimisation, to reduce the production to between 0.015 and 0.03 kg HFC-23/kg HCFC-22 (1.5 to 3 percent) but it is not possible to completely eliminate HFC-23 formation this way (McCulloch, 2007). Furthermore, the extent of the reduction is highly dependent on the process design and the economic environment (measures to reduce HFC-23 can often reduce the process output). In an optimised process HFC-23 production and emissions will, invariably, have been measured; it is not possible to optimise process operation without such measurements and so default values have no meaning in this context for an individual plant. The state of the technological art has been advanced by optimisation of individual plants and that art should have been built into the design of recent plants, suggesting a default emission factor of 0.03 kg HFC-23/kg HCFC-22 (3 percent). These default values have a large uncertainty (in the region of 50 percent). For more accurate assessments, the actual emissions should be determined by Tier 2 or Tier 3 methodology and, if necessary, assigned to previous years using the guidance provided in Chapter 7 of this volume. Should the vent gas be collected for treatment, thermal oxidation has been shown to reduce HFC-23 emission by 99.996 percent (Irving, 2000).

TABLE 3.28 (UPDATED)
HFC-23 DEFAULT EMISSION FACTORS

Technology	**Emission Factor (kg HFC-23/kg HCFC-22 produced)**
Old, unoptimised plants (e.g., 1940s to 1990/1995)	0.04
Plants of recent design, not specifically optimised	0.03
Global average emissions (1978 - 1995)[1]	0.02
For comparison:	
Optimised large plant- requiring measurement of HFC-23 (Tier 3)	*Down to 0.015*
Plant with effective capture and destruction of HFC-23 (Tier 3)	*Down to zero*

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[1] The global average is calculated from the change in atmospheric concentration of HFC-23. It does not discriminate between plant emissions, which range from nothing to greater than 4 percent of the HCFC-22 production.

BOX 3.14
PLANT MEASUREMENT FREQUENCY

The accuracy and precision of the estimates of annual HFC-23 emissions depend on the number of samples (the frequency of sample collection) together with the accuracy of measurement of flowrates and the extent to which discrete flow measurements can represent the total quantity vented. Since production processes are not completely static, the greater the process variability, the more frequently plants need to measure. As a general rule, sampling and analysis should be repeated whenever a plant makes any significant process changes. Before choosing a sampling frequency, the plant should set a goal for accuracy and use statistical tools to determine the sample size necessary to achieve the goal. For example, a study of HCFC-22 producers indicates that sampling once per day is sufficient to achieve an extremely accurate annual estimate. This accuracy goal should then be revised, if necessary, to take into account the available resources. (RTI, Cadmus*,* 1998)

CHOICE OF ACTIVITY DATA

When using the Tier 1 method, production data should be obtained directly from producers. There are several ways producers may determine their production levels, including shipment weights and measuring volume-times-density, using flow meters. These data should account for all HCFC-22 production for the year, whether for sale or for use internally as feedstock, and the plant should describe how the HCFC-22 production rate is determined. In some circumstances, producers may consider plant production data to be confidential. For national-level activity data, submission of HCFC-22 production data is already required under the Montreal Protocol.

COMPLETENESS

It should be possible to obtain complete sampling data because there are only a small number of HCFC-22 plants in each country, and it is standard practice for each plant operator to monitor process efficiencies and hence HFC-23 losses, leading to the adoption of Tier 2 methodology. The destruction efficiencies of thermal oxidisers used to abate HFC-23 are generally high (>99 percent) but it is important to establish the composition of the exit gas in order to ensure that account is taken of emissions of fluorinated greenhouse gases from this point.

DEVELOPING A CONSISTENT TIME SERIES

Emission of HFC-23 from HCFC-22 production should be estimated using the same method for the entire time series and appropriate emission factors. If data for any years in the time series are unavailable for the Tier 3 method, these gaps should be filled according to the guidance provided in Volume 1, Chapter 5.

3.10.1.3 UNCERTAINTY ASSESSMENT

TIER 1

Unlike the other Tiers, where uncertainties are based on measurements and statistics, Tier 1 uncertainties are assessed through expert judgement and an error of approximately 50 percent could be considered for Tier 1 based upon knowledge of the variability in emissions from different manufacturing facilities. An error of this magnitude will completely outweigh the uncertainty in the activity.

TIER 2

Uncertainty of the Tier 2 result is calculated by the root-squared sum of the individual uncertainties in production mass quantity and efficiencies, assuming the carbon and fluorine uncertainties are the same. Where the uncertainties in carbon and fluorine efficiency differ significantly (enough to cause a material difference to the calculated emission), the value with the lower uncertainty should be used throughout the calculation.

Uncertainty in the value derived by Tier 2 methods is much larger than that expected from Tier 3 but is, nevertheless, quantifiable. Typically, for a plant producing about 4 percent HFC-23, the carbon efficiency is in the region of 95 percent and the fluorine efficiency 92 percent. If these efficiencies can be measured to within 1 percent, then the error in the Tier 2 HFC-23 estimate would be less than 20 percent. Estimating efficiencies to this degree of accuracy will require rigorous accounting procedures and that all raw materials and product for sale should be weighed in or out of the facility. Such a regime sets the expected accuracy of the overall activity (for both Tiers 1 and 2); with good accounting and measurement of production by weight, it should be possible to reduce the error in the activity to below 1 percent.

TIER 3

For HFC-23, the Tier 3 method is significantly more accurate than either the Tier 2 measured or Tier 1 default methods. Regular Tier 3 sampling of the vent stream can achieve an accuracy of 1-2 percent at a 95 percent confidence level in HFC-23 emissions and the uncertainty of the Tier 3 (emission-factor-based) result may be similar. In both cases, the uncertainty may be calculated statistically from the uncertainties of the input parameters and, because these methods do not rely on emission factors or activities, the concept of subdividing uncertainty has no validity.

Uncertainty of the estimate is expressed as a coefficient of variance (percent) and, for each of these streams, there will be an uncertainty as a consequence of uncertainties in measured concentration and flowrate and uncertainty in the duration of the flow. The combined uncertainty can be determined analytically and should be calculated using the standard methodology described in Chapter 3 of Volume 1.

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

No refinement.

3.10.2 Emissions from production of fluorinated compounds (other than HFC-23 emissions from HCFC-22 production)

3.10.2.1 INTRODUCTION

The emission of HFC-23 from HCFC-22 manufacture was considered in Section 3.10.1. Section 3.10.2 (this section) considers emissions from other fluorochemical production processes. These emissions include emissions of the intentionally manufactured chemical as well as reactant and by-product emissions. For example, in a national inventory for a fluorochemical plant, significant by-product emissions of SF_6, CF_4, C_2F_6, C_3F_8, C_4F_{10}, C_5F_{12} and C_6F_{14} were reported (United Nations Framework Convention on Climate Change (UNFCCC), 2005). Other examples include the release of by-product N_2O and CF_4 from the production of NF_3 (Tasaka, 2004; 2007), CF_4 from the production of CFC-11 and 12, or of SF_6 from the production of uranium hexafluoride in the nuclear fuel cycle.

Typically, fluorochemicals may be released from chemical processes involving a broad range of technologies and processes[2]:

- Telomerization Process used in the production of fluorochemicals fluids and polymers;
- Photooxidation of tetrafluoroethylene to make fluorochemical fluids;
- Direct Fluorination often used in SF_6 production;
- Halogen Exchange Processes to make HFCs 134a and 245fa and low-boiling-point PFCs like C_2F_6 and CF_4;
- NF_3 manufacturing by direct fluorination;
- Production of uranium hexafluoride;
- Production of fluorinated monomers like tetrafluoroethylene and hexafluoropropylene;
- Production of fluorochemical agrochemicals;
- Production of fluorochemical anesthetics;
- Production of perfluorpolyethers;
- Production of hydrofluoroolefins (HFO) such as tetrafluoropropene and its precursors.

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[2] This list is illustrative.

Halogen exchange processes are extensively used for HFC manufacture, while most PFCs and SF_6 require elemental fluorine, generated electrochemically. In 'electrochemical fluorination' processes, the fluorine is not separated but makes the desired product in the electrochemical cell. In other processes it is separated and subsequently used, either as the elemental gas or as a component of a carrier system, such as CoF_3. Each process will have a different spectrum of emissions, in terms of both chemical nature and quantities, and so a common default emission function is subject to considerable uncertainty.

Potential sources of fluorinated GHG emissions at fluorochemical production facilities include the following: process vents, equipment leaks, and evacuating returned containers. Production-related emissions of fluorinated GHGs occur from both process vents and equipment leaks. Process vent emissions occur from manufacturing equipment such as reactors, distillation columns, and packaging equipment. Equipment leak emissions, or fugitive emissions, occur from valves, flanges, pump seals, compressor seals, pressure relief valves, connectors, open-ended lines, and sampling connections. In addition, users of fluorinated GHGs may return empty containers (e.g., cylinders) to the production facility for reuse; prior to reuse, the residual fluorinated GHGs (often termed "heels") may be evacuated from the container and are a potential emission source. In many cases, these "heels" are contaminated and are exhausted to a treatment device for destruction. In other cases, however, they are released into the atmosphere. The Tier 1 default emission factor is intended to cover emissions for process vents, equipment leaks, and container venting.

It is essential that the existence of potentially emissive plants is identified within each country; hence this step is first in the decision tree (Figure 3.17). The common factor for most of these plants is the use of anhydrous hydrogen fluoride, which is the source of fluorine in halogen exchange processes and in processes that use elemental fluorine. The production and importation of anhydrous hydrogen fluoride can therefore be used as a means of tracing significant producers of fluorochemicals. Note that in some cases, the plant consuming the anhydrous hydrogen fluoride may be supplying fluorinated feedstocks to other plants that themselves produce fluorochemicals and emit GHGs. Further enquiries (see Figure 3.17) can elucidate whether or not there are significant fluorochemical greenhouse gas emissions at the plant consuming the anhydrous hydrogen fluoride and whether or not that plant supplies fluorinated feedstocks to other plants.

Feedstocks commonly used in the production of fluoropolymers are HCFC-22, 1,1 difluoroethlyene, tetrafluoroethylene (TFE), and hexafluoropropylene oxide (HFPO). Their production and imports can therefore be used to identify significant producers of fluoropolymers that may not themselves be consumers of hydrogen fluoride.

In this section, emissions associated with use are not addressed specifically, being counted in the emissions related to consumption (see Chapters 4.5, 6, 7 and 8 in this volume).

3.10.2.2 METHODOLOGICAL ISSUES

CHOICE OF METHOD

It is *good practice* to choose the method using the decision tree shown in Figure 3.17. If the Category 2B9 Fluorochemical Production is identified as *key* and this subcategory is judged to be significant, inventory compilers should consider whether or not emissions are dominated by the production of a sub-set of chemicals, and focus more sophisticated data collection efforts on production of these chemicals. We estimate that 80 fluorochemical production facilities operate among 20 countries world-wide (2004 SRI report; U.S. Environmental Protection Agency (EPA) Greenhouse Gas Reporting Program (GHGRP)). A survey of national producers should not be difficult to compile.

Tier 1

In the Tier 1 methodology, a default emission factor, or a similar number derived for the particular country's circumstances, can be used to estimate national production-related emissions of individual HFCs, PFCs, SF_6 and other fluorinated greenhouse gases. The default emission factors in Table 3.28a are expressed in terms of kg emitted/kg produced). When used in a Tier 1 calculation, the applicable default emission factor is multiplied by the total mass of fluorinated chemical produced.

EQUATION 3.41

TIER 1 CALCULATION OF PRODUCTION-RELATED EMISSIONS

$$E_k = EF_{default,k} \bullet P_k$$

Where:

E_k = production-related emissions of fluorinated greenhouse gas k, kg

$EF_{default,\,k}$ = default emission factor, kg emitted /kg produced

P_k = total production of fluorinated chemical k, kg

The fluorinated greenhouse gas k could be the intended gas being manufactured, an un-intended by-product formed during manufacturing, or a reactant feed. Problems of confidentiality arising from reporting specific component data can be circumvented by providing a single number for total national emissions of each HFC, PFC, SF_6 or other fluorinated GHG. This may be facilitated if data are collected by a third party and reported only as this total.

Tier 2

A mass balance based approach that is based on process efficiencies can be more complicated than for HFC-23 emissions from HCFC-22 plants as there can be a range of by-products responsible for process inefficiency (unlike the case for HCFC-22 where one by-product predominates), as well as loss of the intended product and reactants. However, production efficiency data should exist for each process and, in the absence of a more rigorous estimate, the emissions can be estimated based on the difference between the total mass of the reactants and that of the products. These emissions can then be characterized based on information regarding the chemical composition of the emitted mass. The chemical composition may be determined based on measurements, engineering calculations and assessments, process knowledge, etc. Such an estimate may enable a qualitative decision as to whether or not these emissions are a significant subcategory under a *key category*. Should sufficient measurements of the chemical composition of the emissions exist, this methodology could also be used for estimating emissions for reporting.

The mass balance method is summarized in Equation 3.41a below. If the chemical composition of the mass of material emitted from the process is determined through chemical analysis (e.g., a sample taken from the laboratory-, pilot-, or full-scale process) the Tier 2 estimate is further improved.

EQUATION 3.41A (NEW)

TIER 2 CALCULATION OF PRODUCTION-RELATED EMISSIONS USING A MASS BALANCE APPROACH

$$E_k = \sum_i \sum_j \int_t C_{ijk} \bullet M_{ij}$$

Where:

E_k = total production-related emissions (kg) of fluorinated greenhouse gas k: the sum over all i plants, over all j streams in each plant and integrated over time t.

C_{ijk} = the concentration of fluorinated greenhouse gas k present in emissions from stream j, at plant i, kg/kg

M_{ij} = mass emitted from stream j, at plant i, as determined from a mass balance. This mass determined from the difference in the mass of materials (products, by-products, or reactants) entering and leaving the process, kg

The mass balance method accounts for both vented and leaked emissions, but not emissions from the venting of returned cylinders. In the case of cylinder venting, emissions can be estimated based on the mass of material vented from the cylinder and the chemical composition of the mass.

Tier 3

The Tier 3 methodology is potentially the most accurate estimate and is the sum of factory specific emissions of *each* fluorinated greenhouse gas (reactants, intended product, and by-products) determined using standard methods to estimate the composition and flowrate of gas streams actually vented to atmosphere after any abatement technology. Selected examples of standard methods are Fourier transform infrared spectroscopy (FTIR), gas chromatography and mass spectrometry (GC/MS), and calibrated mass flow meters. The particular standard method used for measurement is chosen based on the type of manufacturing process being monitored. As noted above, emissions from manufacturing can be divided into two categories: process vents and equipment leaks. The total emissions of greenhouse gas *k*, from both process vents and equipment leaks is determined as described by Equation 3.41b.~~.~~

EQUATION 3.41B (NEW)
TIER 3 SUMMATION OF PRODUCTION-RELATED EMISSIONS FROM PROCESS VENTS AND EQUIPMENT LEAKS

$$E_k = E_{kPV} + E_{kEL}$$

Where:

E_k = total production-related emissions of fluorinated greenhouse gas k from process vents and equipment leaks

E_{kPV} = total production-related emissions of fluorinated greenhouse gas k from process vents

E_{kEL} = total production-related emissions of fluorinated greenhouse gas k from equipment leaks

Process vent and equipment leaks are described as follows.

Process Vents

Process vents are typically configured for intermittent or continuous measurement(s) of the concentration, and where a process-vent flow rate exists, emissions can be determined as follows:

EQUATION 3.42 (UPDATED)
TIER 3 DIRECT CALCULATION OF PRODUCTION-RELATED EMISSIONS FROM PROCESS VENTS

$$E_{kPV} = \sum_i \sum_j \int_t C_{ijk} \bullet f_{ijk}$$

Where:

E_{kPV} = total process vent, production-related emissions of fluorinated greenhouse gas k: the sum over all i plants, over all j streams in each plant of the emitted mass flows f and concentrations C and integrated over time t.

Alternatively, process vent emissions can be determined by utilizing a facility- or process-specific emission factor. The emission factor is determined by normalizing the emission rate of the reactants, intended product, and by-products by a more easily (or accurately) measurable parameter, such as feedstock flow rate, as described in Equation 3.38 in Section 3.10.1:

EQUATION 3.43 (UPDATED)
TIER 3 CALCULATION OF PRODUCTION-RELATED EMISSIONS FROM PROCESS VENTS USING A SITE- OR PROCESS-SPECIFIC EMISSION FACTOR

$$E_{kPV} = \sum_i \sum_j \int_t E_{ijk}$$

Where:

E_{kPV} = total process vent, production-related emissions of fluorinated greenhouse gas k: summed over all i plants, over all j streams and integrated over time t.

E_{ijk} = the process vent emissions of fluorinated greenhouse gas k from each plant and stream determined by the facility- or process- specific emission factor based methods, described in Equations 3.38 and 3.39 in Section 3.10.1

For process vents, emissions may be determined based on direct measurements, engineering calculations and assessments, and process knowledge. For continuous processes with significant fluorinated GHG emissions, it is *good practice* to develop site-specific or even process-vent-specific emission factors based on measurements of emissions and activity. For smaller processes and for batch processes, it is *good practice* to develop the specific emission factors based on either measurements or engineering calculations and assessments. Note that, generally, flows are measured volumetrically and should be converted into mass flow (kg/hour) based on the ideal gas law, temperature, pressure and composition; similarly concentration should be converted into compatible units (e.g., kg/kg).

In this case, the flowrates, concentrations and duration should be calculated separately for the periods when the abatement technology is or is not operating and only those that lead to actual emissions should be summed and reported.

Cylinder Venting

In the case of cylinder venting, the Tier 3 approach uses the mass of material vented from the cylinder and the chemical composition of the mass as the basis for the emissions estimate. The chemical composition is typically available from the contents of the cylinder (e.g., stated purity or certificate of analysis). If there is a question regarding the composition of the cylinder contents (e.g., anticipate that impurities are present), then the Tier 3 approach may include actual measurement of the chemical composition of the vented material using an analytical method specified previously in this section.

Equipment Leaks

Emissions from equipment leaks can originate from a variety of process and equipment types; there are a number of different standard methods from which to choose. Three example approaches follow and are based on guidance from US EPA (1995): the Screening Ranges Approach, Correlation Approach, and Unit-Specific Correlation Approach. While these approaches were developed for hydrocarbons primarily, similar equipment is used for fluorochemical production, transfer, and storage and they are therefore appropriate for fluorochemicals. The choice of equipment component used is mostly based on the physical state of the chemical (gas, liquid) and the temperature and pressure of the process stream. For a given set of physical parameters, differences in the chemical properties between hydrocarbon and fluorochemicals are not expected to significantly affect the leak rate from valves, flanges, seals, etc. (See section 2.4.1, 2.4.6, and 2.4.7 in EPA, 1995 for additional information on speciating emissions.) It is, however, important to use appropriate monitoring equipment capable of measuring fluorinated chemicals. For all three approaches, fluorochemicals typically have dramatically different response factors than hydrocarbons, and in some cases, have little response on analytical equipment commonly used for hydrocarbon leak detection.

In the Screening Ranges Approach, two sets of emission factors are combined with corresponding equipment counts to estimate emissions. Emission factors are assigned to pieces of equipment (sources) based on whether a leak detector applied to the source indicates fluorinated GHG concentrations fall above (source greater than, or SG) or below (source less than, or SL) a particular leak concentration definition. These definitions are available from US EPA (1995) for many types of equipment (these US EPA values are for total organic compounds but may be applied to fluorinated GHG).

EQUATION 3.43A (NEW)
TIER 3 CALCULATION OF EMISSIONS FROM EQUIPMENT LEAKS USING A SCREENING RANGES APPROACH

$$E_{gijkEL} = (SG_{ig} \bullet CG_{ig} \bullet C_{gijk}) + (SL_{ig} \bullet CL_{ig} \bullet C_{gijk})$$

Where:

E_{gijkEL} = the equipment leak–related emissions of fluorinated greenhouse gas k in stream j, from plant i, from equipment type g, kg/hr.

SG_{ig} = applicable emission factor for sources with screening values greater than or equal to 10,000 ppmv from equipment type *g* at plant i, kg/hr-source

CG_{ig} = equipment count for sources with screening values greater than or equal to 10,000 ppmv

from equipment type g at plant i.

C_{gijk} = the concentration of fluorinated greenhouse gas k, present in emissions leaking from equipment type g, in stream j, from plant i, kg/kg or L/L

SL_{ig} = applicable emission factor for sources with screening values less than or equal to 10,000 ppmv from equipment type g at plant i, kg/hr-source.

CL_{ig} = equipment count for sources with screening values less than or equal to 10,000 ppmv from equipment type g at plant i.

Use of the actual screening value measurements where available (i.e., the actual concentration in ppm, not only an indication of above or below 10,000 ppmv), with the Correlation Approach is an additional refinement to the Screening Ranges approach. The Correlation Approach utilizes correlations developed by the US EPA (1995) to predict mass emission rate as a function of screening value for a particular equipment type. Equipment types include gas valves, light liquid valves, connectors, and light liquid pump seals.

EQUATION 3.43B (NEW)
TIER 3 CALCULATION OF EMISSIONS FROM EQUIPMENT LEAKS USING A CORRELATION APPROACH

$$E_{gijkEL} = (Slope_g \bullet (SV_{gjk})^{CE_g}) \bullet C_{gijk})$$

Where:

E_{gijkEL} = the equipment leak–related emissions of fluorinated greenhouse gas k, of stream j, from equipment type g, at plant i, kg/hr.

$Slope_g$ = slope of correlation equation for equipment type g. See US EPA (1995).

CE_g = exponent for correlation equation for equipment type g.

SV_{gjk} = screening value for greenhouse gas k, in stream j, from equipment type g.

C_{gijk} = the concentration of fluorinated greenhouse gas k present in emissions leaking from equipment type g, in stream j, from plant i, kg/kg

It is important to ensure the units of the correlation and screening values (SV) are consistent with each other. In the case that the SV value is zero, or the value is higher than the upper limit able to be measured by the portable screening device, default EL_j values in units of kg/hr per equipment type exist.

The third approach for estimating equipment leak emissions is the Unit-Specific Correlation Approach. In the Unit-Specific Correlation Approach, selected mass emission rates are determined by an equipment bagging procedure, and the associated screening value (concentration) is concurrently measured. This set of data is used to develop a unit-specific correlation (i.e., regression equation) between the log base 10 value of the leak/mass rate and screening value for a specific equipment type on a given process unit, as described in Equation 3.43c.

EQUATION 3.43C (NEW)
TIER 3 CALCULATION OF A UNIT-SPECIFIC CORRELATION

$$\log_{10} E_{gijk} = (\beta_0 + \beta_1 \bullet SV_{gijk})$$

Where:

E_{gijkEL} = the equipment leak–related emissions of fluorinated greenhouse gas k, in stream j, and equipment type g, at plant i. kg/hr.

β_0 = intercept of regression equation (determined from the measurements and data gathered using the equipment bagging procedure for the particular equipment).

β_1 = slope of regression equation (determined from the measurements and data gathered using the equipment bagging procedure for the particular equipment).

SV_{gijk} = screening value for greenhouse gas k from in stream j, equipment type g, at plant i.

EQUATION 3.43D (NEW)
TIER 3 CALCULATION OF EMISSIONS FROM EQUIPMENT LEAKS USING A UNIT-SPECIFIC CORRELATION APPROACH

$$E_{gijkEL} = (SBCF_{gijk} \bullet 10^{\beta_0} \bullet (SV_{gijk})^{\beta_1} \bullet C_{gijk})$$

Where:

E_{gijkEL} = the equipment leak–related emissions of fluorinated greenhouse gas k, in stream j, from equipment type g, at plant i. kg/hr.

$SBCF_{gijk}$ = Scale bias correction factor (The SBCF is a function of the mean square error of the correlation in log space, as described in US EPA (1995).

C_{gijk} = the concentration of fluorinated greenhouse gas k present in emissions leaking from stream j, from plant i. kg/kg

The total emissions of greenhouse gas *k*, from equipment leaks is determined as described by Equation 3.43e where emissions are summed over all streams *j*, equipment types *g*, at all plants *i*, over a given time period *t*. Should values of E_{gijk} originate from the Unit-Specific Correlation Approach, special care must be used to ensure that these E_{gijk} are used only for the particular equipment type and plant where they were generated.

EQUATION 3.43E (NEW)
TIER 3 CALCULATION OF PRODUCTION-RELATED EMISSIONS FROM EQUIPMENT LEAKS

$$E_{kEL} = \sum_{i} \sum_{j} \sum_{k} \int_{t} E_{gijkEL}$$

Where:

E_{kEL} = total equipment leak, production-related emissions of fluorinated greenhouse gas k and integrated over time t.

E_{gijkEL} = the equipment leak-related emissions of fluorinated greenhouse gas k in stream j, from plant i, and equipment component type g as determined by the methods, described in Equations 3.43a, 3.43b, or 3.43d.

CHOICE OF EMISSION FACTORS

Tier 1

Tier 1 relies on default emission factors. The default emission factors presented in Table 3.28a are based on a survey of the available literature and, in the case of the last factor, on an analysis of data reported to the US EPA Greenhouse Gas Reporting Program. The first two sets of factors apply to production of SF_6 and NF_3 respectively; the last applies to production of any other fluorochemical. All of the default emission factors assume there is no use of abatement and the default emission factors for SF_6, NF_3, and “other fluorochemicals” include emissions from both process vents and equipment leaks (see Annex 3A.1).

The lower emission factor provided for SF_6 was based on estimated typical emission rates during production; the higher emission factor was found for facilities that also vented residual gas (the “heel”) from containers before refilling them (because their customers, electronics manufacturers, required highly purified SF_6 gas). In countries with SF_6 production, it is *good practice* to apply the lower emission factor if container heels are known to be recycled or destroyed; otherwise, it is *good practice* to apply the higher emission factor.

Both the GHGs emitted and the emission rates for those GHGs (kg per kg of the fluorochemical produced) are shown in the middle column of the table. There is a wide range of substances that may potentially be released during production of fluorochemicals. In some cases, the fluorinated GHGs released during production of a particular fluorochemical have GWPs similar to that of the produced fluorochemical (AFEAS 2004). However, in other cases, the GWPs of the released fluorinated GHGs can be significantly different from that of the produced fluorochemical. The default emission factors presented in Table 3.28a, along with the default composition of emitted fluorinated GHGs in Table 3.28b, reflect both of these situations.

The Tier 1 factors are highly uncertain. Therefore, if emission factors specific to the facility and produced fluorochemical are available, these should be used. Because emission rates vary widely among facilities and processes, caution should be used when applying emission factors measured for a particular fluorochemical at a particular facility to the same fluorochemical at a different facility. However, emission factors measured at other facilities for the same fluorochemical may be used when the process type (see section 3.10.2.1) used to produce the fluorochemical is the same at both facilities, when the treatment of container heels is the same at both facilities, and when the emission factor does not reflect abatement. (Emission factors that reflect abatement should not be used in the Tier 1 method.) Note that an emission factor measured for production of one fluorochemical is not applicable to the production of another, even at the same facility, because different fluorochemicals (even if they are chemically similar, such as two HFCs) are associated with different by-products and different by-product generation rates. Thus, not only the identities, but also the quantities of the GHGs emitted differ.

Some process-specific emission factor data are available from commercially available life cycle assessment software; these emission factors may be used if their source data, calculation methods, and units of measure are well documented.

TABLE 3.28A (NEW)
TIER 1 DEFAULT EMISSION FACTORS FOR FLUOROCHEMICAL PRODUCTION

Fluorochemical Produced	Emission Factor for each Emitted GHG (kg fluorinated GHG emissions/kg fluorochemical produced)	Uncertainty for default emission factor for fluorochemical production
SF_6	0.03 (SF_6)[a] 0.08 (SF_6)[b]	±50% (0.015 to 0.045) ±50% (0.04 to 0.12)
NF_3	0.02 (NF_3)[c] 0.03 (N_2O)[d] 0.01 (CF_4)[d]	±50% (0.01 to 0.03) ±50% (0.015 to 0.045) ±50% (0.005 to 0.015)
All other fluorochemicals	0.04 (see Table 3.28B for composition of emitted mass)[e]	-98% to +470% (0.001 to 0.2)[f]

Source:

[a] O'Connell, 2002.

[b] Suizu, 1999.

[c] Fthenakis, 2010.

[d] Tasaka, 2004; 2007.

[e] As described further in Annex 3A.1 of this Volume, the default emission factor was estimated using data from the US EPA Greenhouse Gas Reporting Program (US EPA, 2017a; 2017b). Briefly, under the Greenhouse Gas Reporting Program, fluorinated GHG emissions are reported annually on a facility basis and include facilities with and without abatement. Depending on the year, 14 to 16 fluorochemical production facilities have reported under the Program. Facilities that abate their emissions report their level of abatement for each process as a range. To develop emission factors on an uncontrolled basis, the pre-abatement emissions of each facility were estimated using the arithmetic averages of the abatement ranges reported by that facility for its processes. Then, for each facility, this estimate was divided by the total quantity of fluorinated gases produced or transformed by that facility to obtain an uncontrolled emission factor for that facility and year. This was done for all six years for which the US EPA had data at the time the factor was developed. For each facility, the emission factors for each year were then averaged over the six years of reporting, and the resulting facility averages were averaged to obtain the default factor above. Because the reporting U.S. facilities use multiple manufacturing methods to produce a wide array of fluorochemicals,[3] averaging the facility-specific emission factors is expected to provide a default emission factor that is applicable where the manufacturing method is unknown, as is often the case in a Tier 1 calculation.

[f] As noted above, emission rates from different manufacturing methods can vary widely, a pattern seen in the variation of the emission factors across the facilities reporting to the U.S. Greenhouse Gas Reporting Program. This variation (summarized here as a 95-percent confidence interval around the arithmetic mean) provides a first order estimate of the uncertainty of the default Tier 1 emission factor. Thus, the default emission factor is broadly applicable, but it is also highly uncertain due to the inherent variability of emission rates across manufacturing methods and produced fluorochemicals.

In addition to the compounds being intentionally produced, a variety of fluorinated GHG by-products can be emitted from fluorochemical manufacturing processes. Emissions of these other fluorinated GHGs can exceed emissions of the compound being intentionally produced. Where the specific fluorinated GHGs emitted are known, inventory compilers should assume that the mass emitted consists of these compounds. Where the specific fluorinated GHGs emitted are not known, it is *good practice* to assume that the mass emitted consists of the fluorinated GHGs listed in Table 3.28b in the proportions provided.

TABLE 3.28B (NEW)
REPRESENTATIVE CHEMICAL COMPOSITION OF THE EMITTED MASS

Fluorinated GHG emitted	Percentage emitted (% of unweighted tonne)[a]
HFC-134a	18
PFC-14 (Perfluoromethane)	18
Perfluorocyclobutane	13
HFC-32	11
HFC-125	11
HFC-23	11

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[3] Fluorochemicals produced in the U.S. and reported to the GHGRP include HFCs, HFEs, PFCs, SF_6, NF_3, other fully fluorinated greenhouse gases, and others. Emissions are also reported from the transformation of some of these substances, as well as CFCs and HCFCs, into other materials such as polymers.

TABLE 3.28B (NEW) (CONTINUED)
REPRESENTATIVE CHEMICAL COMPOSITION OF THE EMITTED MASS

Fluorinated GHG emitted	Percentage emitted (% of unweighted tonne)[a]
HFC-143a	7
PFC-116 (Perfluoroethane)	5
PFC-218 (Perfluoropropane)	4
PFC-5-1-14 (Perfluorohexane, FC 72)	3

Due to rounding, the sum of individual items will not equal 100%.

Source:

[a] To derive this composition, six years of US EPA GHGRP data were sorted, and the chemical species with the highest estimated uncontrolled emissions (in metric tonne) were identified. The weighted average GWP of these emissions is the same as the weighted average GWP of the uncontrolled emissions (other than very low-GWP emissions) estimated for fluorinated gas producers that report to the US EPA.[4] More discussion on the development of the default emissions factor and the representative chemical composition is provided in Annex 3A.1.

Tier 2 and Tier 3

Tier 2 relies on an estimate of the mass of emissions lost from the process, and if available, measurement(s) of the chemical composition of the emitted mass. Tier 3 relies on direct measurements of, and the use of, process- and facility-specific emission factors to determine the quantities of individual fluorinated GHGs released into the atmosphere.

For Tier 2 and Tier 3, it is important to determine and document whether the production facility abates production-related emissions of each fluorinated GHG. If the quantity of gas emitted to the atmosphere is reduced by, for example, thermal treatment of the vent stream, the quantity emitted should be adjusted to account for the destruction efficiency of the oxidiser and the length of time that it is in service. As an example, when a thermal treatment unit is well-operated and well-maintained, it has been shown to reduce HFC-23 emission by 99.996 percent (Irving, 2000). However, the on-line time of the destruction process can also have a significant effect on emissions and should be recorded. For example, in the case of a treatment system with 99 percent removal efficiency, the magnitude of fluorinated GHG emissions would be dominated by the amount of time the gas stream is being treated.

Emission control technologies are used at many facilities to control fluorinated GHG emissions from process vents. Destruction and removal efficiencies (DREs) are generally based on performance testing of emission control devices. Results are expected to vary across process equipment and gas flow rates. To apply a DRE to an emission control device, the device must be specifically designed to abate fluorochemicals. If facilities use other types of abatement devices not designed specifically for fluorinated GHGs, they should assume that its destruction efficiency is 0 percent for fluorinated GHGs. In addition, the inventory compiler must demonstrate through communication with facility managers and subsequent documentation that emissions control technologies are operated and maintained in accordance with manufacturer specifications. The DRE should only apply to that portion of emissions that pass through a properly operating and maintained control device, and DRE should not be applied when control device is bypassed, not operating according to manufacturer specifications, or not maintained in accordance with specifications.

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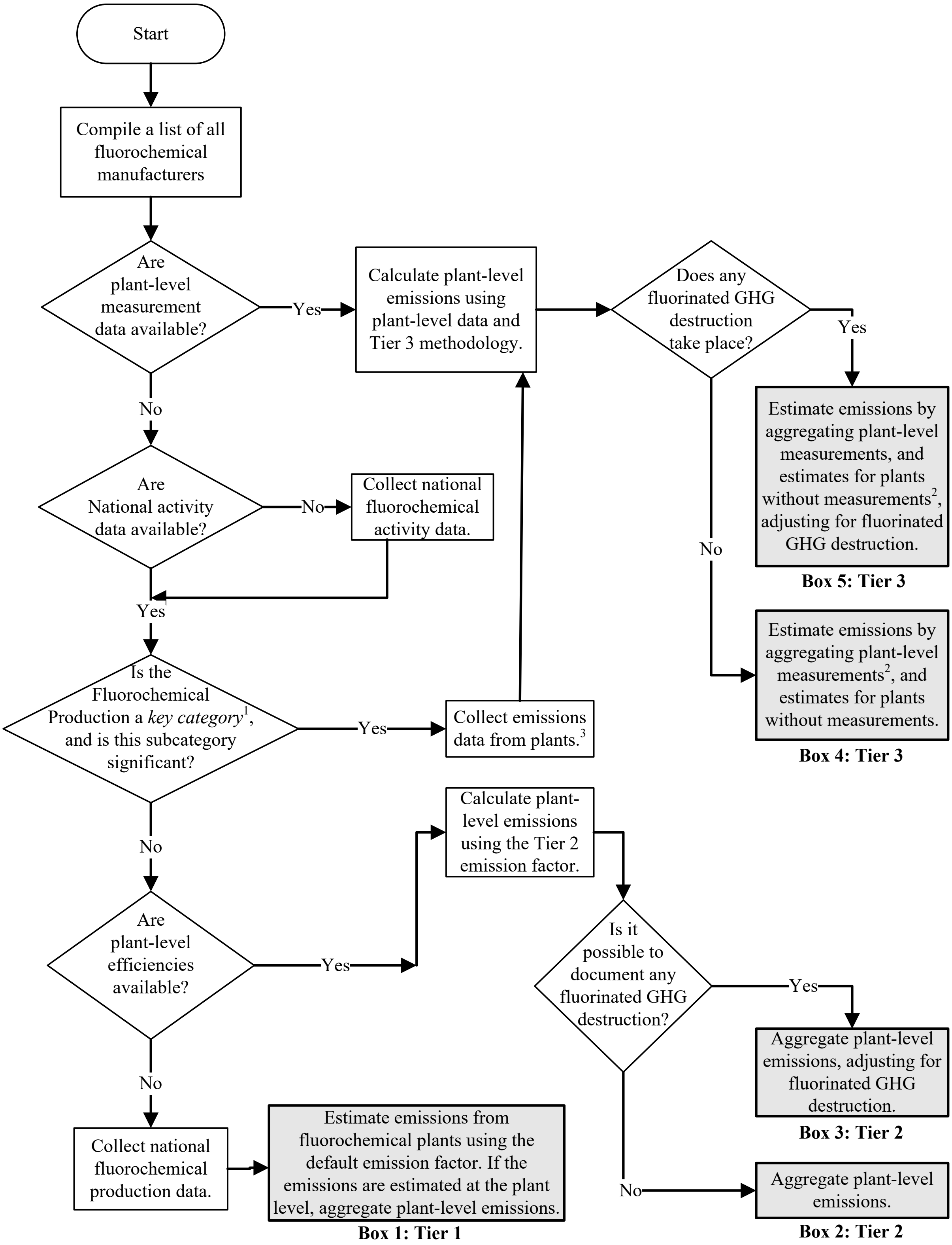
[4] To develop both the mass emission factor in Table 3.28a and the break-out of fluorinated GHGs in Table 3.28b, fluorinated GHGs with GWPs above one were included in the analysis. Fluorinated GHGs with GWPs near one, such as unsaturated HFCs and PFCs, were excluded. This reduced the emission factor in terms of tons emitted/tons produced, but it had negligible impact on the metric tonne of CO_2eq. emitted/metric tonne produced.

Figure 3.17 (Updated) Decision Tree for emissions of fluorinated greenhouse gas from fluorochemical production processes, applicable to product, by-product, reactant, and fugitive



Note:

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

2. If there are Tier 3 data available for some plants, the Tier 1 or Tier 2 methods can be applied to the remainder to ensure complete coverage.

3. Data may be collected as a country study by a third party in order to preserve confidentiality.

CHOICE OF ACTIVITY DATA

For Tier 1, the activity is the annual mass of the desired fluorochemical that is produced. These activity data may be available as total production data for the country or may be available for individual facilities. For Tier 2, the activity is the mass of the produced fluorochemical(s) as well as the consumption of feedstocks. For Tier 3, the activity data for emissions from process vents may be either the annual mass of the produced fluorochemical(s) or the annual mass or quantities of one or more feedstocks consumed, and the activity data for emissions from equipment leaks is the number of potentially leaking equipment components of each type. Individual facilities should have access to the activity data for Tier 2 and Tier 3. For Tier 3, the activity data may sometimes be available from an industry trade group.

Recycling

Recycling of used gas may be done by the producers of new gas or by other recycling firms. Emissions may occur during handling and purification of old gas and handling of recycled gas. Specific emission factors are not available. Thus, *good practice* is to use the same default factor as for new production.

COMPLETENESS

Completeness requires that the national GHG inventory include all GHG emissions from all fluorochemical production processes (including emissions from both process vents and equipment leaks) and any other emission sources (including container venting) at all facilities in the country. It is important to note that significant GHG emissions occur not only from processes and facilities producing fluorinated GHGs (for example, HFCs, PFCs, SF_6, NF_3, and fluoroethers), but also from processes and facilities producing fluoropolymers, which are often produced using HCFC, HFC, PFC, and other fluorochemical feedstocks. For some inventory compilers, identifying smaller producers and, in particular, recycling firms may be a difficult task. However, initial estimates based on the national mass balance of these fluorinated greenhouse gases should identify if production related emissions from such entities provide a sizeable contribution to total national emissions.

DEVELOPING A CONSISTENT TIME SERIES

Both by-product and fugitive emissions of fluorocompounds from production processes should be estimated using the same method for the entire time series and appropriate emission factors. If data for any years in the time series are unavailable for the Tier 3 method, these gaps should be filled according to the guidance provided in Volume 1, Chapter 5.

3.10.2.3 UNCERTAINTY ASSESSMENT

Uncertainty related to use of the Tier 1 default emission factors includes the uncertainty in the activity data and the assumptions made in estimating the destruction efficiency used in the uncontrolled emissions analysis. For Tier 1, the uncertainty in activity data needs to be determined for the reporting country and statistically combined with the uncertainty in the default emission factor. Typically, in a well operated facility, the default uncertainty in activity data should be in the region of 1 percent, assuming that rigorous accounting records are maintained and that production is monitored by weight. There are numerous sources of uncertainty in the default Tier 1 emission factor. One is the uncertainty associated with the fact that true uncontrolled emission rates naturally vary from facility to facility depending on the fluorochemicals produced and the processes used to make them. This variability appears in the US EPA data as differences in the calculated uncontrolled emission factors across facilities, differences that persist over the entire time series. The year-to-year variability seen in the calculated uncontrolled emission factor for any one facility is generally much smaller than this facility-to-facility variability. The uncertainty shown in Table 3.28a for the default EF for any other fluorochemicals reflects this variation among facilities. The 95 percent confidence interval (calculated based on the relative standard deviation among the facilities' emission factors) is ±470 percent. Because there cannot be a negative emission factor on the low side, a value of 0.001 was selected as the lower uncertainty bound, as it is representative of lower emission factor values seen in the data set. This results in an uncertainty range for the Tier 1 default emission factor of 0.001 to 0.2.

Another source of uncertainty for the default EF for any other fluorochemicals is the exact extent to which the emissions from individual processes are controlled by the facilities reporting to the US EPA GHGRP. As noted above, the level of abatement (destruction efficiency, or DE) is reported as a range rather than a point estimate, but a point estimate must be used to back-calculate uncontrolled emissions. Thus, there is uncertainty in the choice of this point estimate and in the uncontrolled emissions used to calculate emission factors for each facility and year. In addition, there is uncertainty regarding the exact mix of fluorinated GHGs that would be emitted from each process without controls. Emissions at the facility level are generally reported by chemical, but emissions at the process level are reported by chemical group. While this provides general process-level information on the nature and GWP of the emitted GHGs, the GHGs that fall into each group vary in their GWPs.

However, both of these sources of uncertainty are mitigated by the large number of data points in the analysis, which come from the large number of processes and significant number of years covered. Thus, the errors related to the destruction efficiency estimated for each individual process and to the mix of gases emitted tend to balance out, and the aggregate uncertainty is reduced. A Monte Carlo analysis indicated that the uncertainty for each facility's uncontrolled emission factor was less than 50 percent.

For Tier 3 emissions, the uncertainty of the measurements should be determined individually and combined (using standard statistical methods) to provide a total uncertainty for the estimate. The methodology is identical to that described for HFC-23 from HCFC-22. In the Tier 2 methodology, the uncertainty both of the measurements of efficiencies and the assignment of losses to individual compounds should be assessed. Because these are liable to produce a much larger uncertainty than that from Tier 3, the utility of Tier 2 is likely to be limited to assessing whether or not by-product fluorochemical emissions are a significant subcategory under *key category*.

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

No Refinement

3.11 HYDROGEN PRODUCTION

Hydrogen (H_2) is a gas with flammable properties similar to natural gas and gasoline (Hydrogen Council, 2017). The main current uses of hydrogen are as raw material in refineries and in the production of ammonia, methanol and other chemicals. Other uses are as an energy carrier in the transport sector, as energy storage and buffer systems in renewable electricity production, as a main constituent in coal gas (city gas) used for heating and cooking, as well as in semiconductor industry processing and welding. Production of hydrogen may yield emissions of carbon dioxide (CO_2), depending on the production method, while combustion or conversion of hydrogen to produce heat and electricity yields zero carbon dioxide emissions. An increase in the production, storage and use of hydrogen is expected in the future, due to an increased demand for low-carbon fuels and technologies.

3.11.1 Introduction

This section describes methodological guidance for estimating emissions from Hydrogen production. The methods are primarily applicable to instances where hydrogen is produced as the main product at a stand-alone facility. Note that where hydrogen is produced as part of a gas mixture (for instance in the case of syngas production – see Box 3.19), or as a by-product or intermediate product within another chemical or petrochemical process, then the GHG emissions should be estimated using methods for the most appropriate main product. For example, hydrogen is commonly produced as a by-product or intermediate product at petroleum refineries and at chemical facilities producing ammonia, methanol, and other products. In these instances, it is *good practice* for inventory compilers to apply the methodological guidance specific to those processes, as provided elsewhere within Volume 2 (Energy) and Volume 3 (IPPU), including:

- Volume 2, section 4.2 Fugitive emissions from oil and natural gas systems (includes guidance for emissions from hydrogen production in petroleum refineries, with resultant GHG emissions to be reported under 1.B.2.a.i);
- Volume 3, section 3.2 Ammonia production (with resultant GHG emissions to be reported under 2.B.1);
- Volume 3, section 3.9 Petrochemical and carbon black production (includes guidance for production of methanol and ethylene, both of which may also generate hydrogen by-product, with resultant GHG emissions to be reported under the appropriate sub-sector(s) of 2.B.8).

Hydrogen Production Technologies

Hydrogen can be produced through a wide range of chemical, thermochemical and biological processes; Table 3.29 below presents an overview of the current status (in terms of scale of production) and associated GHG emissions of each known technology.

The predominant hydrogen production technologies, accounting for more than 95 percent of global hydrogen production, are steam reforming and gasification of fossil fuels (Ogden, 1999; Speirs *et al*., 2017). Steam reforming and gasification are thermochemical technologies using feedstock from fossil or renewable sources, which is combined with heat and catalysts to trigger chemical reactions for transforming the feedstock (for example, natural gas, LPG, naphtha, coal, methanol, biomass and waste) into a gas mixture rich in hydrogen. When hydrogen is the final product (see Box 3.15), a series of enhancement and purification steps yields a highly pure hydrogen output (99.95 percent purity is typical at present).

Production of hydrogen by water electrolysis is widespread, mainly in small-scale plants, and accounts for about 4 percent of current global hydrogen production. Other methods for hydrogen production are currently at a minor or experimental level. Several of the production methods, e.g. water electrolysis and photo induced water splitting, do not generate direct GHG emissions from the hydrogen production process. Others, e.g. steam reforming of ammonia and thermal water splitting, generate no *process* emissions of GHGs but do emit GHGs from stationary *combustion of fuels* to heat the production process, and accordingly these emissions should be reported in the Energy sector.

Biological methods to generate hydrogen are currently at a very small-scale, and typically involve a fermentation process to produce hydrogen, using living microbes such as algae and bacteria. In the production process either fossil or biogenic materials are consumed under anaerobic conditions, and the output products are hydrogen gas containing minor amounts of CO_2, CH_4 and other organic substances, and CO_2 off-gas which may be partly captured by the microbes; at present a maximum of 2 percent CH_4 by mass in the hydrogen product is reported in some anaerobic biological methods (Braga et al 2017). Any CH_4 and CO_2 produced in the process will become a constituent part of the fermentation gas product, and any subsequent emissions from this gas use should be reported in the sector(s) where it is used. Hence, emissions from hydrogen production by biological methods are considered negligible and should not be reported in the hydrogen production sector.

Further development and increased uptake of low-emission hydrogen production methods is anticipated, however, methods using fossil feedstock currently dominate due to economic reasons (Speirs *et al*., 2017).

Hydrogen Production: GHG Emission Sources and Reporting Allocations

There are many different hydrogen production technologies, and their contribution to GHG emissions range from zero direct emissions at the production facility (e.g. water electrolysis) to significant direct GHG emissions (e.g. from steam reforming or gasification of fossil feedstocks). Of the directly emissive technologies, some utilise fossil fuels only *for combustion*, to heat the process, with no *chemical process* GHG emissions associated with the hydrogen production, such as dehydrogenation or thermal water splitting, whilst hydrogen production through steam reforming or gasification of fossil materials does result in both *chemical process* and *combustion*-derived GHG emissions.

Table 3.29 provides information on *best practice* for the reporting allocation of emissions from each technology, and further guidance is as follows:

(i) The GHG emissions from hydrogen production as a pure main product at a stand-alone facility should be reported under the Hydrogen production sector in IPPU. This typically includes GHG emissions from hydrogen production technologies that generate process emissions from fossil feedstocks, i.e. steam reforming or gasification of fossil materials. Hydrogen production methods that generate no direct GHG emissions, such as the electrolysis of water, should not be considered in the IPPU sector;

(ii) It is *good practice* to report under Hydrogen Production all the GHG emissions from steam reforming and gasification of fossil materials, including the *fuel combustion* and *chemical process* emissions from the fuels and feedstock, and to exclude these fuel combustion emissions from the Energy sector, in line with the IPCC methods for other similar chemical processes, such as production of ammonia (2B1) and petrochemicals (2B8).

(iii) Emissions of CO_2 from thermochemical processes such as steam reforming and gasification using *biomass* as feedstock should be reported as a memo item only, to avoid double counting with emissions reported in source categories in Agriculture, Forestry and Other Land Use (AFOLU). If the feedstock contains both fossil and biogenic components (e.g., auto diesel mixed in with biodiesel, waste, etc.), the CO_2 emission should be allocated partly to the Hydrogen production sector and partly to the memo item, relative to the respective fossil and biogenic carbon shares.

(iv) As noted above, where hydrogen is produced as a by-product for sale or as an intermediate product in a source category provided with methodological guidance on GHG emissions from hydrogen production, it is *good practice* to estimate GHG emissions by applying the methodological guidance for the appropriate source category. These source categories include:

   a. Petroleum refineries (Volume 2, section 4.2)

   b. Ammonia production (Volume 3, section 3.2)

   c. Methanol production and ethylene production (Volume 3, section 3.9)

(v) Where GHG emissions arise from production of intermediate or by-product hydrogen (including gas mixtures containing hydrogen) in sectors *not* provided with a methodology for estimating these emissions, it is *good practice* to use one of the methodological approaches provided in Volume 3 IPPU (ammonia, methanol or hydrogen), as follows:

   a. If the feedstock is completely oxidized and the main product does not contain carbon, the methodology for hydrogen production should be used.

   b. If the feedstock is partly oxidized and the main product does not contain carbon, the methodology for ammonia production should be used.

   c. If the main product contains carbon, the methodology for methanol production and ethylene production should be used.

The compiler should use the methodology that minimises uncertainties in the national inventory, transparently note which method(s) are used, and report the GHG emissions in the appropriate source category of the main product for that facility.

(vi) Where hydrogen is produced as part of a hydrogen carrier, or released from such a hydrogen carrier system, the GHG emissions yielded from the process may be allocated to a range of different sectors, according to the carrier type. See Box 3.17 for further details.

(vii) Where activity data for hydrogen production at the national level may combine data from stand-alone facilities and integrated facilities within other sectors, and from emissive and non-emissive technologies, inventory compilers should take care to ensure that gaps and double counting of emissions do not occur.

In light of the range of production technologies, it may be difficult for inventory compilers to obtain fully-resolved activity data by technology, making it difficult to estimate and report GHG emissions consistent with the good practice methods outlined above.

As for all inventory source categories, it is *good practice* to estimate and report emissions from hydrogen production such that inventory uncertainties are minimised, and to minimise the risk of any gaps or double-counts in the reported estimates across Energy and IPPU source categories. In the event that the good practice approach to reporting hydrogen production cannot be achieved due to national circumstances, then inventory compilers should transparently document the methods applied, note where emissions from hydrogen production are included (fully or in part) within Energy and/or other IPPU source categories, and derive uncertainty estimates that reflect the country-specific approach.

See Box 3.16 for details about double counting.

Reporting of GHGs contained within the hydrogen product

Some hydrogen production methods generate GHGs as an unintended constituent of the product. For instance, hydrogen produced by biological processes may contain minor amounts of methane. In these cases, the GHGs are emitted after the product has been sold to an end user, either from the use or fugitive release of the product itself or from the combustion of it. It is *good practice* to estimate GHG emissions using methods specific to the final emission source, and report the emissions in that sector, and not in the Hydrogen production sector.

Carbon Dioxide Capture and Storage

Should CO_2 capture technology be installed and used at a plant where hydrogen is produced from steam reforming or gasification of fossil materials, it is *good practice* to deduct the CO_2 captured in a higher tier emissions calculation. The default assumption is that there is no CO_2 capture and storage (CCS). In most cases, methodologies that account for CO_2 capture should consider that CO_2 emissions captured in the process may be both combustion and process-related. However, in the case of hydrogen production from steam reforming or gasification of fossil materials, no distinction is made between fuel and feedstock emissions with all emissions accounted for in the IPPU Sector. Similarly, all CO_2 captured should be accounted for in the IPPU Sector. For additional information on CO_2 capture and storage, refer to Volume 3, Section 1.2.2 and for more details on capture and storage to Volume 2, Section 2.3.4.

CH_4 and N_2O emissions from hydrogen production

Steam reforming and gasification produce very minor emissions of CH_4 and N_2O, in addition to CO_2 emissions. The available literature indicates that emissions of CH_4 and N_2O are very low, activity data for the process combustion source are likely to be hard to obtain, and the literature evidence is insufficient to establish an estimation method. Hence, no reporting of CH_4 and N_2O is required in this sector.

BOX 3.15 (NEW)
DEFINITIONS

Pure hydrogen and gas mixtures

Pure hydrogen is hydrogen gas that has been purified to meet industry product quality standards. Pure hydrogen is produced by *complete oxidation* of feedstocks or by other technologies (Table 3.29).

Hydrogen that is produced by technologies that *partially oxidize* a hydrocarbon feedstock will also contain other gases (typically CH_4, CO, CO_2, other hydrocarbons) and is defined as a "gas mixture".

Final products and intermediate products

A final product is an intended output product from a production facility. The final product can be either sold as a commercial product or exported offsite for use in another facility. An intermediate product is an output from one production process, which is consumed as raw material or fuel in a later production step at the same facility.

Main products and by-products

A main product is the product defining a facility's sector in the IPCC reporting. As a rule of thumb, the main product is the product generating the highest monetary production value. By-products are all other products made intentionally at the facility. If nothing else is stated, main products and by-products are final products.

Feedstock, raw material and fuel

In this section, feedstock means the total input material in a manufacturing process. Raw material is the part of the feedstock being transformed into the final or intermediate product(s). Fuel is a material combusted to produce heat. The fuel might be derived from the feedstock (i.e. internal energy source) or provided separately (i.e. external energy source).

Table 3.29 (New)
Current hydrogen production methods – status of development and allocation of emissions to sector

Category	Technology	Feedstock	Status of development[1]	Sector	Allocation principle
Pure main product hydrogen	Steam reforming	Fossil	Major	Hydrogen production[2]	Fossil process emissions
		Biofuel	Minor	Memo	Biogenic process emissions
		Waste	Minor and increasing	Hydrogen production[2] /Memo	Fossil/biogenic[3] process emissions
		Methanol	Minor and mature	Hydrogen production[2]	Fossil process emissions
	Gasification	Fossil	Major	Hydrogen production[2]	Fossil process emissions
		Biomass	Minor	Memo	Biogenic process emissions
		Waste	Minor and increasing	Hydrogen production[2] /Memo	Fossil/biogenic[3] process emissions
	Water electrolysis	Water	Moderate and increasing	Not applicable	No direct emissions[5]
	Dehydrogenation	Organic Hydride[6]	Minor	Energy (stationary combustion)	Only combustion emissions
		Ammonia	Minor	Energy (stationary combustion)	Only combustion emissions[4]
	Fermentation	Biomass	Experimental	Not applicable	No direct emissions[5]
	Methane cracking	Natural gas	Minor	Energy (stationary combustion)	Only combustion emissions[4]
	Thermal water splitting	Water	Experimental	Energy (stationary combustion)	Only combustion emissions[4]
	Photo catalytic splitting	Water	Experimental	Not applicable	No direct emissions[5]
	Photo biological splitting	Water	Experimental	Not applicable	No direct emissions[5]
By-product or intermediate product hydrogen[2]	Refining of crude petroleum	All	Major	Energy (fugitive)	Hydrogen produced as by-product or intermediate product
	Ammonia production	All	Major	Ammonia production	Hydrogen produced as by-product or intermediate product
	Methanol production	All	Major	Petrochemical and Carbon Black	Hydrogen produced as by-product or intermediate product
	Ethylene production	All	Minor	Petrochemical and Carbon Black	Hydrogen produced as by-product or intermediate product
	Steel production	All	Minor	Iron and Steel and Metallurgical Coke	Hydrogen produced as by-product or intermediate product
	Caustic soda production	Sodium chloride	Moderate	Not applicable	Produced by electrolysis. No direct emissions[5]
	Fuel cell reforming	Methanol	Experimental	Sector of the end user	Hydrogen produced as an intermediate product
		Fossil	Minor and increasing	Sector of the end user	Hydrogen produced as an intermediate product

TABLE 3.29 (NEW) (CONTINUED)
CURRENT HYDROGEN PRODUCTION METHODS – STATUS OF DEVELOPMENT AND ALLOCATION OF EMISSIONS TO SECTOR

Notes:

[1] Status of development refers to the current situation in a global scale. Major, moderate and minor reflect the amount of industrial hydrogen production. Experimental means that the hydrogen is not yet produced in an industrial scale.

[2] Where hydrogen is produced as a by-product or intermediate product, the emissions are typically already accounted for in the emission estimates for the respective sectors derived using methodological guidance in Volume 3 Energy or Volume 4 IPPU. Emissions from production of hydrogen as part of mixtures with other gases, e.g., syngas, are not covered by this section. See Box 3.15 for the definition of main product, by-product and intermediate product and Box 3.16 about double counting.

[3] Non-biogenic emissions are reported to IPPU and biogenic emissions are reported as a memo item (i.e. not included in the IPPU totals).

[4] No process emissions, as the feedstock does not contain carbon. All emissions arise from combustion of fuels to power the production process.

[5] Only direct emissions (i.e. emissions generated in the production facilities during production) are considered, according to standard IPPU methodology.

[6] In dehydrogenation, the raw material is not consumed. Hence, all emissions come from fuel combusted to produce heat for the reaction.

BOX 3.16 (NEW)
DOUBLE COUNTING, COMPLETENESS AND CROSS-CUTTING ALLOCATION

- In order to avoid double counting, activity data and emissions from production of hydrogen reported in the **Hydrogen production sector** must be excluded from other sectors, i.e. the total quantities of oil, gas, coal and other fossil materials (fuel plus feedstock) used in hydrogen production must be subtracted from the quantity reported under energy use in the Energy sector. Conversely, activity data and emissions from production of hydrogen reported in the **Energy sector** and **IPPU sectors other than Hydrogen production** must be excluded from the Hydrogen production sector.

- Where the level of activity data resolution does not enable separation of the production of hydrogen as a pure product, by-product or gas mixture, then it is *good practice* for compilers to calculate and report emission estimates such that (i) the emission estimates are complete with no double-counting, and (ii) that overall inventory uncertainty is minimised. Further, it is *good practice* to clearly explain the national circumstances, activity data, methods and reporting allocations in inventory submissions.

- In many hydrogen production processes, the same fossil material is used both as raw material for the production process and as fuel combusted to heat the process. It is impractical to seek to distinguish between “fuel” and “feedstock” and to report these emissions separately. Therefore, it is *good practice* to report both the fuel combustion and chemical process emissions in the Hydrogen production sector, and to exclude these fuel combustion emissions from the Energy sector, consistent with the IPPU cross-cutting guidance as presented in Vol. 3 IPPU, Chapter 1.2.1 and Box 1.1.

- To minimise the risk of gaps and double-counts, inventory compilers may need to consult with statistical agencies, trade associations and plant operators as appropriate, to seek to ensure that the hydrogen production activity data does not include any hydrogen derived from non-emissive technologies, nor any production of hydrogen as a by-product or intermediate within facilities that produce other main outputs such as refineries, ammonia and methanol plant where the GHG emissions are already accounted for elsewhere in the inventory.

- Recovered CO_2 might be delivered for downstream use, for instance as raw material in other manufacturing processes or as dry ice (cooling, cleaning, etc.), or sent to a permanent storage. When used in a downstream manufacturing sector, the CO_2 might be embedded into a product (for instance through a chemical reaction) or emitted to the atmosphere. It is *good practice* to report the emission of CO_2 from downstream use in the **downstream IPPU or other sector**, and to subtract the recovered CO_2 from the Hydrogen production sector.

- The downstream use and permanent storage of recovered CO_2 should be transparently described and must be documented in accordance with IPCC Guidelines. It is *good practice* to cross-check that all emissions from downstream use of recovered CO_2 is accounted for in the corresponding downstream sector(s).

BOX 3.17 (NEW)
PRODUCTION AND USE OF HYDROGEN CARRIERS

Hydrogen is a highly volatile gas, which may be transported through a pipeline or in tanks as a compressed gas or as a cryogenic liquid. To facilitate the safe, efficient transport and storage of hydrogen, a carrier chemical may be used. A ‘hydrogen carrier’ is a chemical substance containing hydrogen that is easy to store and transport, from which the hydrogen gas can be extracted through a chemical reaction for use in a downstream sector. Some carriers are recycled for subsequent hydrogen deliveries, while others are consumed in the process where the hydrogen is released.

Some hydrogen carriers are produced with a full load of hydrogen in a single-step process. Other hydrogen carriers are produced and loaded with hydrogen in a two-step process, first as an “empty” carrier. Subsequently, the hydrogen (normally produced at a different plant) is embedded into the empty carrier through a chemical reaction.

The hydrogen carrier is transported to a downstream facility, for example a refuelling station, where the hydrogen is released by a chemical reaction (dehydrogenation) and filled into a vehicle or machine, or the hydrogen carrier itself is filled into a fuel cell, in which the hydrogen (H_2) is released and consumed.

The different types of hydrogen carrier chemicals have the GHG emissions from their production and use allocated to different sectors.

Organic hydrides

Hydrogen can be reacted with aromatic substances such as benzene and toluene to form liquid organic hydrides.

The emissions from the manufacturing of hydrogen should be allocated to the *Hydrogen production* sector, while the emissions from production of the aromatic substances used as “empty carriers” should be allocated to the *Petrochemical and carbon black* sector.

The reaction releasing hydrogen at the downstream facility produces no process emissions of GHGs. Instead, the organic hydride is converted back to the original aromatic substance and transported to the hydrogen production facility to embed more hydrogen, in a circular material flow pattern. The hydrogen-releasing reaction requires heat, which might be produced by combustion of fossil fuels. In such cases, the emitted CO_2 should be allocated to the Energy sector (stationary combustion).

Ammonia

Ammonia (NH_3) is a hydrogen-rich gas that can be cooled down and/or compressed into a liquid and transported to a downstream facility or fuel cell. There the hydrogen (H_2) may be released by a chemical reaction (dehydrogenation).

The emissions from the ammonia production process should be allocated to the *Ammonia production* sector, even though the purpose of producing the ammonia is to derive hydrogen for downstream use.

For the use of ammonia as hydrogen carrier, no emissions should be allocated to the *Hydrogen production* sector. The reaction releasing hydrogen at a downstream facility produces no process emissions of CO_2, since the ammonia contains no carbon. Fossil combustion emissions from the hydrogen releasing reaction should be allocated to the Energy sector (stationary combustion).

Methanol

Methanol (CH_3OH) is a hydrogen-rich liquid that can be transported to a downstream facility, where the hydrogen may be released by a chemical reaction (e.g. steam reforming).

The emissions from the methanol production should be allocated to the *Petrochemical and carbon black* production sector, even though the purpose of producing the methanol is to derive hydrogen for downstream use.

The process at the downstream facility to release hydrogen from the methanol generates process emissions of CO_2. These emissions should be reported in the *Hydrogen production* sector, using the estimation methods provided for this sector.

Consumption of methanol in direct methanol fuel cells yields CO_2 emissions, but hydrogen (H_2) isn’t involved in the reactions. Accordingly, these CO_2 emissions should be reported in the Energy sector.

3.11.2 Methodological issues

The predominant methods for hydrogen production at present are steam reforming and gasification of fossil feedstocks. Both technologies oxidise the feedstock during the process itself and also in combustion to heat the process, releasing CO_2.

Technologies for producing hydrogen from fossil or biogenic feedstocks in an open, aerobic environment can be placed in either of two categories, according to the degree of conversion of the *feedstock carbon*: complete oxidation technologies and partial oxidation technologies.

Complete oxidation technologies convert all feedstock carbon into CO_2 (except for a small residue of solid carbon), and they have hydrogen as the main product. The CO_2 emissions can be estimated from feedstock consumption or hydrogen production data.

Partial oxidation technologies convert parts of feedstock carbon into CO_2, and they result in gas mixtures having hydrogen as a constituent. In several industries using hydrogen as a raw material, partial oxidation technologies[5] are often used to produce an intermediate mixture of hydrogen and CO (e.g. syngas production, see Box 3.19), as also CO is needed for raw material. To regulate the H_2:CO ratio, hydrogen might be separated from the mixture as a by-product and burnt for fuel or used externally (e.g. sold for use in a downstream sector).

A list of production methods and allocation by sector is given in Table 3.29.

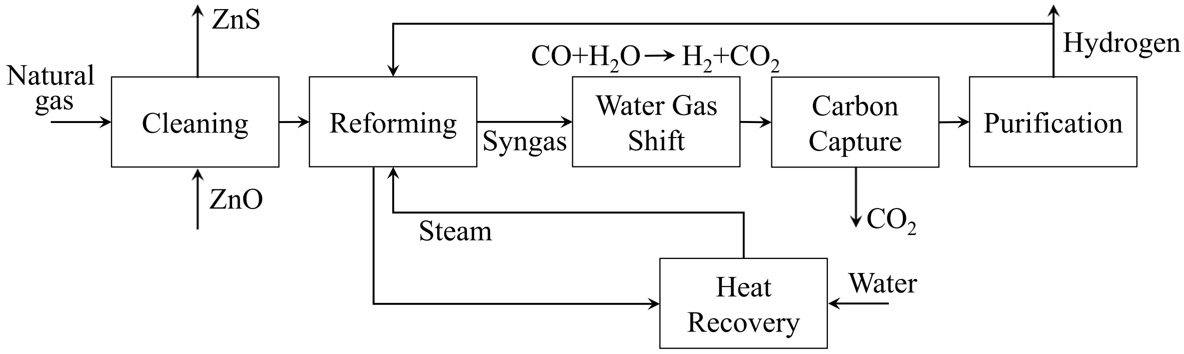
COMPLETE OXIDATION TECHNOLOGIES

The main complete oxidation technologies are steam reforming of natural gas and fossil liquids (Figure 3.18) and gasification of coal and lignite (Figure 3.19). Both production processes have several steps, in order to maximise the hydrogen output. The first one partially oxidizes the feedstock carbon and generates a gas mixture containing hydrogen, carbon monoxide and, in the case of gasification of coal and lignite, solid carbon. The next step further oxidizes the carbon by a water gas shift reaction, yielding even more hydrogen. An integrated combustion reaction using feedstock (or gasified feedstock) as fuel, or in some cases a support fuel, provides energy to produce steam for the water gas shift reaction.

Other feedstocks are sometimes used as well, though in a very small scale at present. The feedstock material may be fossil carbon in origin, biogenic carbon in origin, or a mixture of fossil and biogenic (such as the use of mixed wastes as a feedstock), but the underlying chemistry to derive the hydrogen is the same and hence the GHG emission estimation methods are similar.

In both the hydrogen producing (overall) reaction and the combustion reaction there is a close to 1:1 molar relation between the produced CO_2 and the carbon contained in the feedstock. The only exception is a small amount of solid carbon residue disposed of as waste.

Figure 3.18 (New) Hydrogen production via steam reforming with water gas shift reaction



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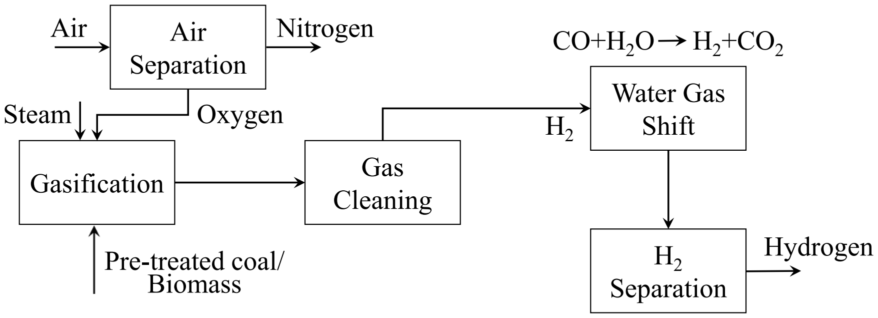
[5] Partial oxidation technologies include all technologies partially oxidizing the feedstock. One of these is commonly called "partial oxidation".

Figure 3.19 (New) Hydrogen production via gasification with water gas shift reaction[1]



Note:

[1] The flue gas from the H_2 separation step, containing CO and methane, is combusted in a boiler to produce heat (i.e. steam).

Source:

Matzen *et al*., 2015; The National Energy Technology Laboratory, 2017.

BOX 3.18 (NEW)
CHEMICAL REACTIONS IN HYDROGEN PRODUCTION BY COMPLETE OXIDATION TECHNOLOGIES

Steam reforming of natural gas (overall reactions):

1a) Reforming: $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$

1b) Combustion: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

Steam reforming or gasification of other fossil or biogenic feedstocks (overall general formulas):

2a) Reforming or gasification: $C_aH_bO_c + (2a\text{-}c)*H_2O \rightarrow a*CO_2 + (2a+0.5b\text{-}c)*H_2$

2b) Combustion: $C_aH_bO_c + (a+0.25b\text{-}0.5c)*O_2 \rightarrow a*CO_2 + 0.5b*H_2O$

Gasification of waste (overall general formulas):

3a) Gasification:

$C_aH_bO_cN_dS_e + (2a\text{-}c+2d+2e)*H_2O \rightarrow a*CO_2 + d*NO_2 + e*SO_2 + (2a+0.5b\text{-}c+2d+2e)*H_2$

3b) Combustion:

$C_aH_bO_cN_dS_e + (a+0.25b\text{-}0.5c+d+e)*O_2 \rightarrow a*CO_2 + d*NO_2 + e*SO_2 + 0.5b*H_2O$

In all these overall reactions the ratio of consumed feedstock carbon atoms to produced CO_2 molecules is 1:1. The molar relation between each reforming or gasification reaction and the subsequent combustion reaction depends on the efficiency of the production process, and the ratio of produced hydrogen to produced CO_2 varies accordingly (Braga *et al*., 2017; Trane *et al*., 2012).

PARTIAL OXIDATION TECHNOLOGIES

Partial oxidation technologies are reforming and gasification technologies producing hydrogen and carbon monoxide (CO) in closed systems with a sub-stoichiometric supply of oxygen. The process typically includes the first reaction step in a complete oxidation technology producing a mixture of hydrogen and CO, and it might include one or more subsequent steps (e.g., a water gas shift reaction) to obtain the desired ratios for the two gases. Purified gases, including H_2, may be produced as a by-product.

Emissions from technologies partially oxidizing the feedstock, including syngas production (see Box 3.19 below), are not covered by the estimation methods in this section, to avoid double counting with other sectors.

BOX 3.19 (NEW)
SYNGAS

Syngas is a gas mixture containing hydrogen, carbon monoxide and sometimes smaller amounts of CO_2, methane and other gases as well. The hydrogen to carbon monoxide molar ratio varies from about 0.5 to 5 depending on the feedstock. Syngas is produced by different technologies partially oxidizing the feedstock, including steam reforming, gasification, partial oxidation and auto-thermal reforming, in the presence of heat. The feedstock may be natural gas, coal, liquid refinery residues or other carbon containing materials.

Syngas is typically used as an intermediate product in refineries, ammonia, methanol or other chemical industries, but production for offsite use as an energy product or separated into its single gases also occurs. Surplus hydrogen might be separated from the syngas and purified into a by-product to obtain a specific H:CO ratio in the syngas for use in the production process of the main product. Emissions from syngas production are not covered by the estimation methods in this section. Methods to estimate GHG emissions from syngas intermediate and hydrogen by-product production in petroleum refineries, ammonia, methanol and other chemical production are provided in the respective Energy and IPPU sectors.

Source:
Abbas, 2018; Copeland *et al*., 2005; Maurstad, 2005; The Global Syngas Technologies Council, 2018; The National Energy Technology Laboratory, 2018, 2002.

OTHER PRODUCTION METHODS

Biological methods including fermentation produce hydrogen by using living microbes like algae and bacteria. In the production process either fossil or biogenic raw materials are consumed under anaerobic conditions, and the output products are hydrogen containing minor amounts of CO_2, methane and other organic substances, and CO_2 off-gas. Methane and other GHGs being produced along with the hydrogen are parts of the product and should be reported in the sector(s) where it is used. The CO_2 off-gas is assumed balanced by the CO_2 taken up by the microbes, and should not be reported.

Production of hydrogen by other technologies than those mentioned above, including water electrolysis, photo induced water splitting, steam reforming of ammonia and thermal water splitting, are typically without process GHG emissions, and emissions from these production methods should not be reported in the Hydrogen production sector.

3.11.2.1 CHOICE OF METHOD

The choice of method will depend on the availability of activity data, as shown in the decision tree (Figure 3.20). The Tier 1c, 2c and 3c methods are based on feedstock consumption data, while the Tier 1b, 2b and 3b methods are based on hydrogen production data. The Tier 1a method is based on hydrogen production data on a total national or regional level, or hydrogen production capacity if production data are not available. There is no Tier method labelled 2a or 3a on this section.

If all relevant activity data are available, it is *good practice* to choose the method having the lowest overall uncertainty. A higher Tier method has a lower uncertainty than a lower one, and the Tier *c* method normally has a lower uncertainty than the Tier *b* method at the same Tier level. The Tier 1a method has the highest uncertainty.

CO_2 released from hydrogen production may be recovered, either for capture and storage or for use in other downstream manufacturing industries. In all emission estimation methods, it is *good practice* to subtract recovered CO_2 from the estimated emissions in the Hydrogen production sector and to include the emissions in the respective downstream IPPU sector(s). If the recovered CO_2 is sent to permanent storage, it is *good practice* to subtract the recovered CO_2 from the Hydrogen production sector.

The estimation methods below are presented using energy units (GJ) for feedstock activity data, and mass units (tonne) for the hydrogen production data. Where these parameters are reported in different units at the national or facility level (e.g. volume, mass) then unit conversions consistent with national or facility data or IPCC defaults may be applied.

Guidance on how to allocate the GHG emissions to the correct sector is given in the previous section (3.11.1).

TIER 1 METHOD

The Tier 1 methods use *national or regional level activity data* together with *default factors* and data on recovered CO_2 to derive emissions. This method should be used if country-specific factors (Tier 2) or plant specific activity data and factors (Tier 3) are not available and hydrogen production is not a *key category*. The activity data are consumption of feedstock (Tier 1c) or production of hydrogen (Tier 1b and 1a). In the Tier 1c and 1b methods the activity data are split by type of feedstock, and feedstock specific factors in Table 3.30 should be used. In the Tier 1a method total national or regional activity data and the general default factors in Table 3.30 could be used.

The CO_2 emissions are estimated as follows:

EQUATION 3.44 (NEW)
CO_2 EMISSIONS FROM HYDROGEN PRODUCTION – TIER 1C

$$E_{co_2} = \sum_j (FC_j \bullet CCF_j \bullet 44/12) - R_{co_2}$$

EQUATION 3.45 (NEW)
CO_2 EMISSIONS FROM HYDROGEN PRODUCTION – TIER 1B

$$E_{co_2} = \sum_j (HP_j \bullet FRF_j \bullet CCF_j \bullet 44/12) - R_{co_2}$$

EQUATION 3.46 (NEW)
CO_2 EMISSIONS FROM HYDROGEN PRODUCTION – TIER 1A

$$E_{co_2} = HP \bullet FRF \bullet CCF \bullet 44/12 - R_{co_2}$$

Where:

E_{CO2} = emissions of CO_2, tonne

FC = feedstock consumption in production of pure hydrogen as main product, GJ

HP = pure hydrogen produced as main product, tonne

FRF = feedstock requirement per unit of output, GJ feedstock / tonne hydrogen produced

CCF = carbon content factor, tonne C / GJ feedstock

j (subscript) = feedstock *j*

R_{CO2} = CO_2 recovered, tonne

Aggregate feedstock consumption data (FC) or hydrogen production data (HP) from national statistics may be used in the Tier 1 methods. For feedstock data obtained in tonne, conversion to GJ can be done by using the default calorific values in the Ch. 1. Vol. 2 of *2006 IPCC Guidelines* [6]. If data on feedstock consumption or hydrogen production are not available, hydrogen production capacity data might be combined with a utilization factor to estimate the hydrogen production in the Tier 1a method. The selection of activity data should aim to minimise the risk of any gaps or double-counting (Box 3.16) with hydrogen production from non-emissive technologies, or from partial oxidation technologies and fuel combustion already included in other inventory estimates.

The feedstock requirement factor (FRF) converts the production of hydrogen into the corresponding consumption of feedstock. The default values are given in Table 3.30. The carbon content factor (CCF) converts the feedstock into carbon equivalents, while 44/12 converts the carbon into CO_2.

It is *good practice* to estimate of the fossil and biogenic emissions separately, based on the respective fossil and biogenic carbon shares, and to allocate the biogenic emissions to a memo item and exclude it from the Hydrogen production sector. If the biogenic part cannot be estimated, it is *good practice* to assume that all feedstock is fossil. If no data on recovered CO_2 could be obtained, it is *good practice* to assume that the recovery is zero.

If activity data and factors for all the Tier 1 methods are available, it is *good practice* to use the method giving the lowest uncertainty.

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[6] For plastic gasification the NCV value is given in the footnote to Table 3.30.

TIER 2 METHOD

The Tier 2 methods use *national or regional level activity data* together with *country-specific factors* and data on recovered CO_2 to derive emissions, and should be used when hydrogen production is a *key category* and plant-specific activity data are not available. The activity data used in the Tier 2 method must be split by type of feedstock. The CO_2 emissions are estimated as follows:

EQUATION 3.47 (NEW)
CO_2 EMISSIONS FROM HYDROGEN PRODUCTION – TIER 2C

$$E_{co_2} = \sum_{j} (FC_j \bullet CCF_j \bullet 44/12) - R_{co_2}$$

EQUATION 3.48 (NEW)
CO_2 EMISSIONS FROM HYDROGEN PRODUCTION – TIER 2B

$$E_{co_2} = \sum_{j} (HP_j \bullet FRF_j \bullet CCF_j \bullet 44/12) - R_{co_2}$$

Where:

E_{CO2} = emissions of CO_2, tonne

FC_j = feedstock consumption in production of pure hydrogen as main product, feedstock j, GJ

HP_j = pure hydrogen produced as main product, feedstock j, tonne

FRF_j = feedstock requirement per unit of output, feedstock j, GJ feedstock / tonne hydrogen produced

CCF_j = carbon content factor, feedstock j, tonne C / GJ feedstock

R_{CO2} = CO_2 recovered, tonne

The equations used in the Tier 2 methods are equal to those used in the Tier 1 method labelled the same letter, the only difference between the two Tier levels being that country-specific factors are needed at the Tier 2 level. Aggregate hydrogen production data (HP_j) or feedstock consumption data (FC_j) from national statistics may be used in the Tier 2 method. If activity data and factors for both Tier 2 methods are available, it is *good practice* to use the method giving the lowest uncertainty. It is *good practice* to use feedstock requirement factors (FRF_j) reflecting whether internal or external energy sources are used to heat the process. If no information on internal vs. external energy source is available, it is *good practice* to use FRF_js for internal energy sources and to note that the information is missing. Double counting with other sectors should be avoided (Box 3.16).

The FRF_j converts the production of hydrogen into the corresponding consumption of feedstock. The carbon content factor (CCF_j) converts the feedstock into carbon equivalents, while 44/12 converts the carbon into CO_2.

It is *good practice* to estimate of the fossil and biogenic emissions separately, and to allocate the biogenic emissions to a memo item and exclude it from the Hydrogen production sector. A fuel containing a fossil and a biogenic part should be split according to the respective fossil and biogenic carbon shares. If country-specific factors and/or an adequate split of the activity data by type of feedstock are not available and Hydrogen production is not a *key category*, it is *good practice* to use the Tier 1 method.

TIER 3 METHOD

The Tier 3 methods use *process- and plant-level activity data and factors* together with data on recovered CO_2 and stored amounts of solid carbon to derive emissions. The CO_2 emissions are estimated as follows:

EQUATION 3.49 (NEW)
CO_2 EMISSIONS FROM HYDROGEN PRODUCTION – TIER 3C

$$E_{co_2} = \sum_{j,n} (FC_{j,n} \bullet CCF_{j,n} \bullet 44/12) - (R_{co_2} + S_c \bullet 44/12)$$

EQUATION 3.50 (NEW)
CO_2 EMISSIONS FROM HYDROGEN PRODUCTION – TIER 3B

$$E_{co_2} = \sum_{i,j,n} (HP_{i,j,n} \bullet FRF_{i,j,n} \bullet CCF_{j,n} \bullet 44/12) - (R_{co_2} + S_c \bullet 44/12)$$

Where:

E_{CO2} = emissions of CO_2, tonne

$FC_{i,j.n}$ = feedstock consumption in production of pure hydrogen as main product, process i and feedstock j and plant n, GJ

$HP_{i,j,n}$ = pure hydrogen produced as main product, process i and feedstock j and plant n, tonne

$FRF_{i,j.n}$ = feedstock requirement per unit of output, process i and feedstock j and plant n, GJ feedstock / tonne hydrogen produced

$CCF_{i,j,n}$ = carbon content factor, process i and feedstock j and plant n, tonne C / GJ feedstock

R_{CO2} = CO_2 recovered, tonne

S_C = stored solid carbon, tonne

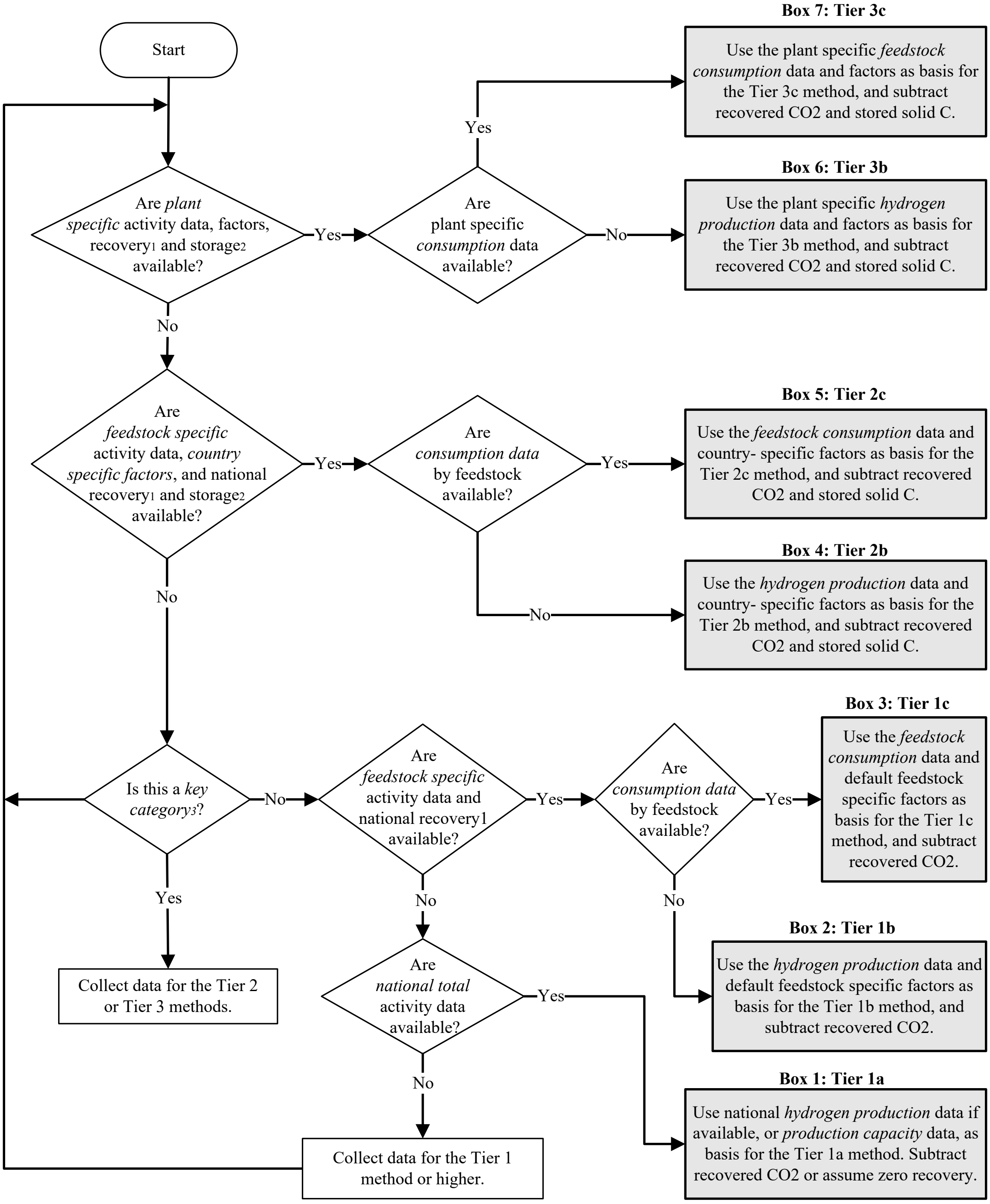
Plant, process and feedstock specific activity data and factors should be obtained from the hydrogen producers. Double counting with other sectors should be avoided (Box 3.16). If activity data and factors for both Tier 3 methods are available, it is *good practice* to use the method giving the lowest uncertainty.

The FRFs should take into account whether or not the fuel used to heat the process is derived from the feedstock (i.e. internal or external energy source). Emissions from fossil and biogenic fuels should be estimated separately, and the biogenic emissions should be allocated to a memo item and excluded from the Hydrogen production sector. Fuels containing a fossil and a biogenic part should be split according to the respective fossil and biogenic carbon shares.

Stored solid carbon here refers to solid carbon or coke formed unintentionally during the production process and disposed of as waste (i.e., not combusted at the production facility). Where no information on the carbon content in the stored solid carbon is available, it is *good practice* to assume that it is pure carbon. It is *good practice* to exclude stored solid carbon from the estimated emissions in the Hydrogen production sector. In the Hydrogen production sector, stored solid carbon does not include recovered CO_2 sent to permanent storage.

If plant, process and feedstock specific activity data and factors are not available and emissions from hydrogen production is a *key category*, it is *good practice* to use a Tier 2 method. If emissions from hydrogen production is not a *key category*, a Tier 1 method may be used.

Figure 3.20 (New) Decision tree for estimation of CO_2 emissions from hydrogen production



Note:

[1] Recovery = annual mass of CO_2 recovered from the hydrogen production emissions.

[2] Storage = annual mass of solid C generated in the hydrogen production emissions and disposed of as waste.

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

3.11.2.2 CHOICE OF EMISSION FACTORS

The feedstock requirement factor (FRF) converts the production of hydrogen into the corresponding consumption of feedstock (raw material and fuel). The carbon content factor (CCF) converts the amount of feedstock in GJ into tonne of carbon.

TIER 1 METHOD

In the Tier 1c method, it is *good practice* to use the default feedstock specific CCFs in Table 3.30, and in the Tier 1b it is *good practice* to use the default feedstock specific FRFs and CCFs. These default values often represent midpoint or mean values of data sets (as determined by expert analysis). In the Tier 1a method, it is *good practice* to use the default FRF_j and CCF_j for the feedstock *j* giving the highest combined value (FRF_j * CCF_j) for the factors. This feedstock *j* should be among the commonly used feedstock types in the country, and the FRF_j and CCF_j should be used for the entire production. If no qualitative information on feedstock types is available, the general default factors might be used. The general default factors are weighted averages of the respective feedstock specific factors, based on global production figures.

TABLE 3.30 (NEW)
DEFAULT FEEDSTOCK REQUIREMENT FACTORS AND CARBON CONTENT FACTORS FOR HYDROGEN PRODUCTION[1,2]

Production Process	Feedstock Requirement Factor (FRF) (GJ feedstock/tonne H_2) ± Uncertainty[1]	Carbon Content Factor (CCF)[2] (tonne C / GJ feedstock)		
Steam reforming		**Default**	**Lower**	**Upper**
Natural gas reforming	165 (± 10%)	0.0153	0.0148	0.0159
Liquified petroleum gas reforming	165 (± 15%)	0.0172	0.0168	0.0179
Naphtha reforming	165 (± 15%)	0.0200	0.0189	0.0208
Methanol reforming	165 (± 20%)	0.0188	0.0186	0.0190
Biosteam reforming, other liquid (bioethanol)	175 (± 20%)	0.0217	0.0183	0.0260
Gasification				
Coal gasification (coking coal)[3]	215 (± 20%)	0.0258	0.0238	0.0276
Plastic[4] gasification	185 (± 10%)	0.0200	0.0160	0.0240
Mixed waste gasification (non-biomass fraction)	275 (± 15%)	0.0250	0.0200	0.0330
Wood waste gasification	260 (± 10%)	0.0305	0.0259	0.0360
Wood sludge gasification	195 (± 15%)	0.0305	0.0259	0.0360
Black liquor gasification	150 (± 10%)	0.0260	0.0220	0.0300
General				
Default	175 (± 30%)[5]	0.0183[6]	0.0148[6]	0.0276[6]

Notes:

1 When uncertainty range is not given in the referenced literature for a given factor, a default uncertainty of ±20% is chosen. When only one literature value is found, a default minimum uncertainty of ±15% is chosen.

2 The factors are also found in Table 1.3 Default values of carbon content in Volume 2.

3 Hydrogen production from coal is currently dominated by use of coking coal as feedstock. Where coal of other quality is used, then it is *good practice* in the Tier 1 method to: (i) apply the FRF for coking coal with an uncertainty range of ±30% when the Tier 1b method is used, and (ii) apply a default CCF that reflects the specific coal type (e.g. lignite, sub-bituminous, other bituminous) as presented in Table 1.3 of Volume 2.

4 Mixed plastic. For CCF the value for "other petroleum products" in Vol.2 Ch. 1 Table 1.3 is used. NCV = 32.0 MJ/kg.

5 Estimated by weighted average of natural gas (49%), LPG/naphtha (29%) and coal (18%), current production methods, based on global production statistics (remaining 4% is mainly produced by electrolysis of water). Uncertainty set to cover the ranges of these three feedstock types, which are by far the most common at present.

6 Estimated by weighted average of natural gas (49%), LPG/naphtha (29%) and coal (18%), current production methods, based on global production statistics (remaining 4% is mainly produced by electrolysis of water). Lower uncertainty range is from steam reforming of natural gas, upper uncertainty range is from gasification of coal.

Source:

Amgad *et al*., 2013; API, 2009; Cormos, 2011; DOE, 2017; Edwards *et al*., 2014; Geissler, *et al*., 2001; Iwasaki, 2003; JARI, 2011; Schiebahn *et al*., 2015; Sørensen, 2011; Themelis *et al*., 2011; The Pacific Northwest National Laboratory, 2017; US Department of Energy, 2017; Wallman *et al*., 1998.

TIER 2 METHOD

For the Tier 2c method it is *good practice* to use country-specific CCFs, and to quality check these factors against the default factors in Table 3.30.

For the Tier 2b method, it is *good practice* to use country-specific FRFs and CCFs, and to quality check these factors against the default factors in Table 3.30 to ensure good factor quality.

TIER 3 METHOD

Plant-level activity data on total fuel and feedstock requirement combined with CCF or hydrogen production combined with CCF and FRF by production technology and feedstock type provide the most rigorous data for calculating CO_2 emissions from hydrogen production. In the Tier 3 methods, it is *good practice* to use plant and feedstock specific CCFs, or plant, process and feedstock specific FRFs and CCFs, and to quality check these factors against the default factors in Table 3.30 to ensure good factor quality. The carbon content (CCF) is a key emission factor variable for deriving the quantity of CO_2 emissions in all Tier methods. Derivation of emissions using plant-level hydrogen production also depends on an accurate estimate of the fuel requirement per unit of output (FRF), along with information on the other variables.

3.11.2.3 CHOICE OF ACTIVITY DATA

For all methods, it is good practice to gather activity data on hydrogen production from national or regional data sources (e.g. statistical agencies, regulatory agencies, plant operators, trade associations, researchers) in order to minimise the risk of gaps and double-counting in the inventory (Box 3.16). Data on CO_2 recovered from hydrogen production (for use downstream, or to storage) should also be sought. It is *good practice* to use the Tier method giving the lowest overall uncertainty.

TIER 1 METHOD

National or regional level activity data may be used in the Tier 1 methods:

- In the Tier 1c method, *feedstock consumption data* by type of feedstock should be used;
- In the Tier 1b method, *hydrogen production data* by type of feedstock should be used;
- In the Tier 1a method, *total hydrogen production data* should be used.

If feedstock consumption or hydrogen production data are not available for the Tier 1c method, production capacity data may be used instead. If the inventory compiler can document that utilisation for a year was below capacity, it is *good practice* to multiply the total national or regional production capacity by a default capacity utilisation factor of 80 percent ± 10 percent (i.e., a range of 70-90 percent) through the entire time-series, or a country-specific capacity utilisation factor. If production capacity data are used for the base year and actual production data are used for later years, a country-specific capacity utilisation factor should be used for all years with production capacity data. It is *good practice* to estimate this capacity utilisation factor as the actual hydrogen production divided by the production capacity of at least one overlapping year adjacent to the years with production capacity data.

It is *good practice* to obtain the biogenic share of the feedstock, to estimate the CO_2 emissions to be excluded from the Hydrogen production sector and reported in a memo item. If the biogenic share cannot be obtained, it is *good practice* to assume that all feedstock is fossil.

Where feedstock data are obtained in tonnes, the default calorific values in Ch. 1, Vol. 2 of *2006 IPCC Guidelines* can be used to convert to energy units.

TIER 2 METHOD

The Tier 2 methods requires the same activity data as the Tier 1 method labelled with the same letter (i.e. the same sub-Tier). The biogenic share of the feedstock should be obtained from the producers, and the estimated biogenic CO_2 emissions should be excluded from the Hydrogen production sector and reported in a memo item.

TIER 3 METHOD

The Tier 3 methods require the collection of plant-level activity data by production method and type of feedstock, including plant-level data on recovered CO_2, where applicable. Production capacity data should not be used. The biogenic share of the feedstock should be obtained from the producers, to estimate the CO_2 emissions to be excluded from the Hydrogen production sector and reported in a memo item.

Where access to plant-level data may be limited due to confidentiality, then inventory compilers should refer to guidance presented in Volume 1, Chapter 2 *Approaches to Data Collection*.

3.11.2.4 COMPLETENESS

In countries where only a subset of plants report data for the Tier 3 method or where there is a transition from Tier 2 to Tier 3, it may not be possible to report according to Tier 3 for all facilities during the transition. Where data for the Tier 3 method is not available for all plants, Tier 2 could be used for the remaining plants. If a mix of Tiers is used, it is *good practice* to report the lower Tier as the applied method. If the estimation uses a mix of *c* and *b* Tiers, it is *good practice* to report as method the one giving the highest uncertainty.

To avoid double counting, emissions from the production of hydrogen as a by-product or intermediate product being reported under other sectors, including Ammonia production and Methanol production (IPPU), Petroleum refining (Energy), must be excluded from hydrogen production.

Recovered CO_2 which is used in downstream sectors or sent to permanent storage should be subtracted from hydrogen production, to avoid double counting with downstream sectors.

Biogenic CO_2 emissions should be excluded from the Hydrogen production sector and allocated to a memo item, to avoid double counting with the AFOLU sector.

See Box 3.16 for more details on double counting and gaps.

3.11.2.5 DEVELOPING A CONSISTENT TIME SERIES

Recalculation of CO_2 emissions should be made for all years whenever emission calculation methods are changed (e.g., if the inventory compiler changes from the use of default values to actual values determined at the plant level). If plant-specific data on hydrogen production and consumed feedstock, and data on recovered CO_2 and stored C, are not available for all years in the time series, it will be necessary to consider how current data can be used to recalculate emissions for previous years. It may be possible to apply current factors to data from previous years, provided that the production technology has not changed substantially.

Recalculation is required to ensure that any changes in emissions trends are real and not an artefact of changes in estimation methods. It is *good practice* to recalculate the time series according to the guidance provided in Volume 1, Chapter 5.

3.11.3 Uncertainty assessment

3.11.3.1 EMISSION FACTOR UNCERTAINTIES

It is *good practice* to obtain uncertainty estimates at the same level (i.e. national, regional or plant) as the activity data. In case of plant level data, the uncertainty should be lower than uncertainty values associated with default values. The same applies to country-specific factors.

Feedstock requirement factors (FRFs): Uncertainty in the default FRFs arise from variation between plants in how efficiently the hydrogen is produced. Three factors are decisive to the level of uncertainty: 1) the process efficiency, i.e. how much fuel is combusted for process heat per tonne of produced hydrogen, 2) the chemical composition of the feedstock, i.e. the hydrogen to carbon ratio, and 3) the specific energy content of the feedstock. Feedstock specific factors have lower uncertainty than the general default factor, because the latter contain the variation in process efficiency, chemical composition and specific energy content between different types of feedstock. Plant specific factors have even lower uncertainties. Estimation methods using FRFs (Tier *b* and *a* methods) have higher overall uncertainty than methods not using the fuel requirement factors (Tier *c* methods), *ceteris paribus*, because the Tier *b* and *a* methods include one uncertain element (FRF) that is not included in the Tier *c* methods.

Carbon content factors (CCFs): Uncertainty in the default CCFs is resulting from variation in 1) the chemical composition of the feedstock, i.e. the hydrogen to carbon ratio, and 2) the specific energy content of the feedstock. Uncertainty arise from variation in composition and energy content of a specific material used as feedstock (for example between different types of coal), and from variation in composition and energy content of feedstocks with a heterogeneous composition (for example waste). Feedstock specific factors have lower uncertainty than the general default factor, because the latter contain the variation between different types of feedstock. Plant specific factors have even lower uncertainties.

In the Tier 1a method, if the highest default CCF value among the feedstock types used in the country is used for the entire production, a country-specific uncertainty estimate or alternatively a default *increase* in the remaining uncertainty of 20 percentage points in the downward direction (only) should be used.

3.11.3.2 ACTIVITY DATA UNCERTAINTIES

Where the activity data are obtained at the plant-specific level, uncertainty estimates may be obtained directly from the hydrogen producers. These activity data are likely to be highly accurate (i.e., with uncertainty as low as ±2 percent). This includes uncertainty estimates for feedstock use (Tier *c* methods) or hydrogen production (Tier *b* and *a* methods), as well as CO_2 recovered and stored solid carbon. Data that are obtained from national statistical agencies usually do not include uncertainty estimates. It is *good practice* to consult with national statistical agencies to obtain information on any uncertainty. Where national statistical agencies collect data from the population of hydrogen production facilities, uncertainties in national statistics are not expected to differ from uncertainties established from plant-level consultations. Where uncertainty values are not available from other sources, a default value of ±5 percent can be used for activity data from national statistical agencies.

If plant-specific data are not available for all years in the time series, and current data are used to recalculate emissions for previous years, the uncertainty in emission estimates might increase due to changes in production technology. It is *good practice* to increase the uncertainty values accordingly.

Where uncertainty values are not available from other sources, a default increase of ±20 percent in the uncertainty can be used for previous reference years estimates based on data on current years.

Where estimates are made to split the fossil and biogenic parts of a mixed feedstock in the Tier 1 and 2 methods, a default uncertainty of ±5 percent should be added to the biogenic part if it is based on reported figures, and ±20 percent if it is estimated. The same uncertainty, in absolute amounts, should be added to the fossil part.

3.11.4 Quality Assurance/Quality Control (QA/QC), Reporting and Documentation

3.11.4.1 QUALITY ASSURANCE/QUALITY CONTROL

It is *good practice* to conduct quality control checks as outlined in Volume 1, Chapter 6. More extensive quality control checks and quality assurance procedures are applicable, if higher tier methods are used to determine emissions. Inventory compilers are encouraged to use higher tier QA/QC for *key categories* as identified in Volume 1, Chapter 4.

Comparison of emission factors

Inventory compilers should check if the estimated factors are within the range of default factors, and also ensure that the emission factors are consistent with the values derived from analysis of the process chemistry. For example, the CO_2 generation rate based on natural gas should not be less than 5.46 tonne of CO_2 per tonne of hydrogen produced[7]. If the emission factors are outside of the estimated range of default factors, it is *good practice* to assess and document the plant-specific or country-specific conditions that account for the differences.

Comparison of activity data

It is useful to collect and report activity data comprising both process input data (feedstock consumption) and process output data (hydrogen production), to control the relation between them.

It is *good practice* to cross-check that all emissions from downstream use of recovered CO_2 is accounted for in the corresponding downstream IPPU or other sector(s).

Plant-specific data check

The following plant-specific data are required for adequate auditing of emissions estimates at the Tier 3 level:

- Calculations and estimation method;
- List of assumptions;
- Documentation of any plant-specific measurement method, and measurement results;

QC procedures in use at the site should be directly referenced and included in the QC plan. If the measurement practices were not consistent with QC standards, the inventory compiler should reconsider the use of these data.

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[7] Method: 44.011 tonne CO_2 / 8.064 tonne H = 5.46 tonne of CO_2 per tonne of H_2 produced, based on molar weights of 12.011 (C), 16.00 (O), 1.008 (H) and 100 percent production yield (i.e. no by-products produced, no fuel combustion to produce heat and no feedstock loss in the production process).

3.11.4.2 REPORTING AND DOCUMENTATION

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Volume 1, Section 6.11.

Some examples of specific documentation and reporting that may be relevant to this source category are provided below:

- Description of the method used;
- Number of hydrogen main product production plants;
- Feedstock requirement factors;
- Carbon content factors;
- Feedstock consumption data;
- Production data;
- Production capacity;
- CO_2 recovery data;
- Downstream use and permanent storage of recovered CO_2;
- Stored solid carbon data;
- Any other assumptions.

Ideally, plant operators should supply this information to the inventory compiler for compilation, and also archive the information at the site. Plant operators should also log and archive the measurement frequencies and instrumental calibration records where actual plant measurements are made.

Where such inventory data (e.g. plant- or company-specific production data) may be considered confidential (e.g. where there are only one or two producers in a country), then inventory compilers should refer to guidance presented in Volume 1, Chapter 2 *Approaches to Data Collection*. In these cases, operators and the inventory compiler should seek to determine the level of aggregation at which information can be reported while still protecting confidentiality. Detailed information including instrumentation records should still be archived at the plant level.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

ANNEX 3A.1 DEFAULT EMISSION FACTORS FOR SECTION 3.10.2 EMISSIONS FROM PRODUCTION OF FLUORINATED COMPOUNDS (OTHER THAN HFC-23 EMISSIONS FROM HCFC-22 PRODUCTION)

This annex provides background information for the Tier 1 default emission factors for fluorinated greenhouse gases (GHG) from fluorochemical production, that are provided in section 3.10.2 in the *2019 Refinement* to the *2006 IPCC Guidelines*. The first section discusses the default emission factors for SF_6 and NF_3 production based on literature search, and the second section discusses the default emission factor estimated from the data reported to the U.S. Greenhouse Gas Reporting Program.

EXECUTIVE SUMMARY

The Tier 1 default emission factor for production of fluorinated gases other than SF_6 and NF_3 was developed based on emissions and throughput (production and transformation) information reported to the U.S. Greenhouse Gas Reporting Program (GHGRP). The factor is intended to represent uncontrolled emissions. Under the GHGRP, fluorinated GHG emissions are reported annually on a facility basis and include facilities with and without abatement. Depending on the year, 14 to 16 fluorochemical production facilities have reported under the Program. Facilities that abate their emissions report their level of abatement for each process as a range. To develop emission factors on an uncontrolled basis, the pre-abatement emissions of each facility were estimated using the arithmetic averages of the abatement ranges reported by that facility for its processes. Then, for each facility, this estimate was divided by the total quantity of fluorinated gases produced or transformed by that facility to obtain an uncontrolled emission factor for that facility and year. This was done for all six years for which the US EPA had data at the time the factor was developed. For each facility, the emission factors for each year were then averaged over the six years of reporting, and the resulting facility averages were averaged to obtain the default factor. Because the reporting U.S. facilities use multiple manufacturing methods to produce a wide array of fluorochemicals, averaging the facility-specific emission factors is expected to provide a default emission factor that is applicable where the manufacturing method is unknown, as is often the case in a Tier 1 calculation.

The uncertainty of the default emission factor was assessed using several methods, including sensitivity analyses, Monte Carlo analysis, and statistical analyses. As discussed further below in section 3A.1.5, these analyses showed that the selected factor was robust despite uncertainties in the reported data, such as the reporting of destruction efficiencies as a range rather than a single value. However, the analyses also indicated that the uncertainty in the emission factor for any single facility is quite large, and is dictated by the fact that true uncontrolled emission rates naturally vary from facility to facility depending on the fluorochemicals produced and the type of manufacturing method used to produce them.

3A.1.1 BACKGROUND INFORMATION FOR SECTION 3.10.2 TIER 1 DEFAULT EMISSION FACTORS – FROM THE LITERATURE

The literature shows a broad range of emission factors for different gases and even for the same gas when it is produced for different applications. For SF_6 produced in Japan, a factor of 0.08 kg emitted/kg produced was found for facilities whose customers require highly purified SF_6 gas (e.g., semiconductor manufacturing). The emission factor is relatively large because of handling losses during disposal of residual gas (i.e., the 'heel' that is not used or recycled) in returned cylinders (Suizu, 1999). An SF_6 emission factor has been reported as 0.03 kg emitted/kg of sales (O'Connell, 2002).

U.S. and Japanese NF_3 manufacturers have reported an emission factor for NF_3 emissions of 0.02 in 2009, with a goal of eventually achieving an emission factor of 0.005 kg emitted/kg produced (it is not known whether the 0.005 factor is based on pre-abatement emissions or controlled, post-abatement emissions) (Fthenakis, 2010). CF_4 and N_2O are generated as a by-product during NF_3 manufacture, and N_2O and CF_4 can be formed at rates of 0.03 kg emitted/kg produced and less than 0.01 kg emitted/kg produced, respectively, relative to the mass of NF_3 formed during electrolysis (these emission factors are on an uncontrolled, pre-abatement basis) (Tasaka, 2004; 2007). Some process-specific emission factor data are available from commercially available life cycle assessment software; these EFs may be acceptable should sufficient documentation of their units, source data, and calculation exist.

In another reference focused on SF_6 produced in Germany, an emission factor of 0.002 kg emitted/kg of the total quantity of SF_6 produced was found for facilities whose customers do not require highly purified SF_6 gas (e.g., electrical equipment, insulated windows) (Preisegger, 1999). Unfortunately, it is not known whether the 0.002

kg emitted/kg produced factor is based on pre-abatement emissions or controlled, post-abatement emissions, and therefore it should not be used for Tier 1 estimates. The authors note the value here for informational purposes and to acknowledge that the data were reviewed for the Tier 1 methodology.

3A.1.2 BACKGROUND INFORMATION FOR SECTION 3.10.2 TIER 1 DEFAULT EMISSION FACTORS – ALL OTHER FLUORINATED GHG

3A.1.2.1 Source of Data

The U.S. GHGRP[8] requires certain facilities that emit greenhouse gases (GHGs) and certain suppliers of fossil fuels and industrial GHGs to report their emissions or supplies (along with other relevant data) annually to the US Environmental Protection Agency (EPA). In general, reporting requirements apply to facilities or suppliers that meet or exceed thresholds that are equivalent to emissions of 25,000 metric tonne of CO_2 equivalent (CO_2eq.) per year. Facilities and reporters collect data for the calendar year and report those data to EPA electronically in the following year by March 31.[9] The US EPA verifies[10] the data and then publishes it. The GHGs covered include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), and other fluorinated gases (e.g., nitrogen trifluoride, hydrofluoroethers [HFEs], perfluorinated amines, etc.).

The default emission factor for fluorochemical production is based on data reported under two sections of the GHGRP regulation—subpart L, Fluorinated Gas Production, and subpart OO, Suppliers of Industrial Greenhouse Gases—for reporting years (RY)[11] 2011 to 2016. Under subpart L, facilities that produce a fluorinated gas (other than HCFC-22[12]) must report their fluorinated GHG emissions from the production and transformation of fluorinated gases, from venting of residual fluorinated GHGs from containers, and from destruction of previously produced fluorinated GHGs. The emissions reported from production and transformation include both emissions from process vents and emissions from equipment leaks. Under subpart OO, fluorinated GHG suppliers (including fluorinated GHG producers) must report the quantities of each fluorinated GHG that they produce, transform, destroy, import, or export.

3A.1.2.2 Data Used in Development of the Fluorinated GHG Emissions Factor

The emission factor was developed from: (1) the emissions from production and transformation processes and emissions from venting of residual fluorinated GHGs from containers, and (2) the quantities of fluorinated GHGs produced and transformed. Facilities reporting emissions under subpart L provide information on emissions from production and transformation processes at two levels of aggregation and in two metrics:

- For the facility as a whole, emissions are provided by specific fluorinated GHG compound in metric tonne where the facility makes more than one product and where the emissions of that compound equal or exceed 1,000 metric tonne CO_2eq. across all processes. Where total emissions of a compound across all processes are less than 1,000 metric tonne CO_2eq., emissions are reported by fluorinated GHG group[13] in metric tonne CO_2eq. Where the facility makes only one product, emissions are reported by compound when that compound is the same as the product; otherwise they are reported by fluorinated GHG group in metric tonne CO_2eq.
- For each production and transformation process at the facility, emissions are reported by process and fluorinated GHG group in metric tonne CO_2eq.

The global warming potentials (GWPs) used to calculate CO_2-equivalent emissions are drawn from the IPCC Fourth Assessment Report (AR4), IPCC Fifth Assessment Report (AR5), or then a default GWP is used. For

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[8] The GHGRP regulation can be found in the U.S. Code of Federal Regulations (CFR) at Title 40, Part 98. For background information on and data from the GHGRP, please see <https://www.epa.gov/ghgreporting>

[9] Mandatory Reporting of Greenhouse Gases. Final rule. (74 FR 56260). October 30, 2009.

[10] For information on how EPA verifies data submitted under the GHGRP, please see <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

[11] The term "reporting year (RY)" refers to the year in which the emissions occurred.

[12] Facilities that produce HCFC-22 are required to report their emissions under a separate part of the GHGRP, Subpart O. The emission factor being developed here is intended to apply to production of fluorochemicals other than HCFC-22 (which is covered in section 3.10.1 of the *F*), and therefore emissions from HCFC-22 production are not discussed further here.

[13] There are twelve fluorinated GHG groups, each of which encompasses a set of GHGs with roughly similar atmospheric behaviour, including similar GWPs and atmospheric lifetimes. These include, e.g., fully fluorinated GHGs such as PFCs and SF_6, HFCs with two or fewer hydrogen-carbon bonds, HFCs with more than two carbon-hydrogen bonds, unsaturated HFCs and PFCs, etc. (See Table A3.1.3 for a full list.) Compounds that do not have GWPs in either the Fourth Assessment Report (AR4) or AR5 are assigned a default GWP that is generally based on the average GWP for the fluorinated GHG group of which the compound is a member.

most fluorinated GHG groups, the default GWP is the average of the GWPs of all the fluorinated GHGs in that group that have GWP values in AR4 or AR5.[14] Where we use emissions reported in CO_2eq. in our calculations, we back-calculate the emissions in metric tonne using the same set of GWPs used to calculate the CO_2eq. emissions.

For the processes, facilities also report the range into which the destruction efficiency (DE) of each process falls. (The DE is based on the extent to which emissions from process vents are controlled. Emissions from equipment leaks are not included in the DE calculation.) Table 3A.1.1 provides the DE ranges available for facilities to report and the DE assumptions for each.

TABLE 3A.1.1 (NEW)
DESTRUCTION EFFICIENCY RANGE VALUES USED TO ESTIMATE PRE-ABATEMENT EMISSIONS FOR PRODUCTION AND TRANSFORMATION PROCESSES

DE ranges	Lower Bound	Upper Bound	Arithmetic Mean of Bounds	Geometric Mean of Bounds
>=0% to <75%	0.0	0.75	0.375	0.500
>=75% to <95%	0.75	0.95	0.85	0.888
>=95% to <99%	0.95	0.99	0.97	0.978
>=99%	0.99	0.9999	0.995	0.999

Facilities reporting emissions of residual fluorinated GHGs from container venting report emissions in metric tonne of each fluorinated GHG.

The activity data for the emission factor was compiled from reporting of the quantities of fluorinated GHGs produced and transformed that were reported under subpart OO.

A3.1.2.3 Calculation of Emissions from Production and Transformation Processes

a. Actual Emissions by Specific Fluorinated GHG for Production and Transformation Processes

Actual emissions of specific fluorinated GHGs reported under subpart L for production and transformation processes are provided in Table 3A.1.2. Table 3A.1.2 provides actual emissions by specific fluorinated GHG for production and transformation processes in metric tonne, and also provides actual GWP-weighted emissions by specific fluorinated GHG for production and transformation processes in metric tonne CO_2eq. Actual emissions are those emissions that actually occur to the atmosphere and reflect the level of control for the process. These totals include only the portion of production and transformation process emissions that are reported by specific fluorinated GHG (approximately 98 percent of production and transformation emissions in metric tonne CO_2eq.).[15]

b. Actual Emissions by Fluorinated GHG Group

Actual emissions of fluorinated GHGs reported under subpart L are provided by fluorinated GHG group for each production and transformation process. Table 3A.1.3 provides actual fluorinated GHG emissions in metric tonne CO_2eq. by fluorinated GHG group. The group totals include all emissions from production and transformation processes.

c. Estimated Emissions Prior to Control by Fluorinated GHG Group

Uncontrolled emissions (i.e., pre-abatement emissions) for production and transformation processes were estimated based on the destruction efficiency (DE) range provided by facilities when they reported on each process, along with the actual fluorinated GHG emissions reported in metric tonne CO_2eq. Because facilities provide the range in which the DE falls rather than the exact DE, an assumption of the true DE must be made.

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[14] For fluorinated GHG groups that have average GWPs below one, including unsaturated HFCs and PFCs, fluorotelomer alcohols, and compounds with carbon-iodine bonds, a default value of one is used, but as discussed further below, these compounds are excluded from this analysis.

[15] The tables in this discussion and subsequent estimated pre-abatement emission discussions exclude compounds with GWPs near or below 1 (i.e., unsaturated PFCs, HFCs, etc.; fluorotelomer alcohols; and fluorinated GHGs with carbon-iodide bonds) because these compounds account for only 0.01 percent of the GWP-weighted emissions reported under subpart L and, as discussed further in section A3.1.5, including them introduces large uncertainties into the emission factor expressed in units of metric tonne.

TABLE 3A.1.2 (NEW)
ACTUAL EMISSIONS FROM PRODUCTION AND TRANSFORMATION PROCESS REPORTED BY SPECIFIC FLUORINATED GHG UNDER SUBPART L OF THE GHGRP (CONSIDERING CONTROLS) (APPROXIMATELY 98 PERCENT OF P/T PROCESS EMISSIONS IN METRIC TONNE CO_2 EQUIVALENT), METRIC TONNE AND METRIC TONNE CO_2 EQUIVALENT^{A}

Fluorinated GHG Name	2011	2012	2013	2014	2015	2016	Sum Total, tonne	% tonne	Cumulative %	2011	2012	2013	2014	2015	2016	Sum Total, tonne CO_2eq.	% tonne CO_2eq.	Cumulative %
HFC-134a	266	222	208	203	227	147	1,273	20%	20%	380,008	317,799	297,074	290,333	324,151	210,574	1,819,938	5.0%	5.0%
HFC-23	191	214	198	112	81	53	849	13%	33%	2,829,581	3,166,284	2,934,831	1,661,087	1,191,554	778,851	12,562,188	34.4%	39.4%
HFC-125	152	151	156	151	136	63	808	12%	45%	533,042	528,308	545,053	527,997	475,389	219,482	2,829,271	7.7%	47.1%
HFC-32	155	165	152	116	130	91	808	12%	58%	104,652	111,119	102,620	78,408	87,501	61,176	545,475	1.5%	48.6%
HFC-143a	136	127	128	100	93	102	685	11%	68%	607,421	566,428	570,420	446,846	413,610	456,470	3,061,194	8.4%	57.0%
PFC-14 (Perfluoromethane)	60	77	58	47	46	54	342	5%	73%	445,137	568,391	428,165	346,613	336,266	402,576	2,527,148	6.9%	63.9%
HFC-245fa	48	49	49	50	41	41	278	4%	78%	49,595	49,965	50,048	51,510	42,477	42,371	285,966	0.8%	64.7%
Perfluorocyclobutane	53	35	26	29	28	52	223	3%	81%	546,574	362,868	268,346	296,849	290,191	535,633	2,300,460	6.3%	71.0%
HFC-227ea	26	25	35	24	25	23	158	2%	84%	84,275	81,365	112,449	76,572	81,943	72,729	509,332	1.4%	72.4%
PFC-116 (Perfluoroethane)	21	20	40	17	23	2	123	2%	86%	250,244	246,574	485,921	207,274	284,305	21,572	1,495,890	4.1%	76.4%
Nitrogen trifluoride	31	28	20	16	15	13	122	2%	87%	531,201	482,591	336,165	272,076	261,263	218,992	2,102,289	5.8%	82.2%
Octafluorotetrahydrofuran	19	25	40	23	6	5	117	2%	89%	188,440	253,010	395,575	232,025	56,124	48,225	1,173,399	3.2%	85.4%
Hexafluoropropylene oxide	11	17	19	20	23	18	109	2%	91%	114,620	172,341	190,459	197,199	233,900	179,593	1,088,112	3.0%	88.4%
PFC-218 (Perfluoropropane)	12	7	48	16	3	3	89	1%	92%	106,887	62,557	424,737	143,241	28,298	23,976	789,696	2.2%	90.6%
Pentafluoro(trifluoromethyl)-cyclopropane	10	8	10	11	19	15	75	1%	93%	102,885	82,428	103,221	112,075	192,068	152,615	745,292	2.0%	92.6%
HFE-449sl, (HFE-7100) Isomer blend	11	11	12	9	9	11	62	1%	94%	3,191	3,264	3,578	2,734	2,598	3,195	18,559	0.1%	92.6%
PFC-5-1-14 (Perfluorohexane, FC 72)	12	8	8	10	13	6	57	1%	95%	109,192	76,500	73,980	95,154	118,276	56,068	529,169	1.4%	94.1%
HFC-152a	9	9	12	0	0	21	51	1%	96%	1,089	1,152	1,491	0	0	2,633	6,366	0.0%	94.1%
Trifluoromethyl sulphur pentafluoride	8	9	19	5	3	2	45	1%	97%	136,465	166,270	332,625	92,038	47,636	29,748	804,783	2.2%	96.3%
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	0	0	4	7	6	15	33	1%	97%	3,019	3,162	24,892	42,564	41,909	97,311	212,857	0.6%	96.9%

Table 3A.1.2 (New) (Continued)
Actual emissions from production and transformation process reported by specific fluorinated GHG under Subpart L of the GHGRP (considering controls) (approximately 98 percent of P/T process emissions in metric tonne CO_2 equivalent), metric tonne and metric tonne CO_2 equivalent

Fluorinated GHG Name	2011	2012	2013	2014	2015	2016	Sum Total, tonne	% tonne	Cumulative %	2011	2012	2013	2014	2015	2016	Sum Total, tonne CO_2eq.	% tonne CO_2eq.	Cumulative %
2H-perfluoro(5-methyl-3,6-dioxanonane)	4	5	3	2	2	6	21	0%	98%	7,776	9,072	6,125	3,462	4,604	11,015	42,053	0.1%	97.0%
Trifluoromethanesulfonyl fluoride	3	4	6	4	2	1	20	0%	98%	6,552	8,400	12,221	7,502	3,111	2,799	40,584	0.1%	97.1%
HFC-236fa	2	3	5	3	2	2	17	0%	98%	22,152	33,285	47,912	28,497	18,093	14,821	164,760	0.5%	97.6%
PFC-3-1-10 (Perfluorobutane)	2	2	6	3	1	2	15	0%	98%	17,853	13,349	54,566	23,017	9,143	18,817	136,746	0.4%	97.9%
Perfluorodiethyl ether	2	3	2	1	2	2	11	0%	99%	16,779	29,448	21,421	13,619	16,460	16,236	113,963	0.3%	98.3%
Perfluorobutanesulfonyl fluoride	1	1	1	1	1	5	10	0%	99%	2,431	1,674	2,091	1,840	2,658	10,155	20,850	0.1%	98.3%
Sulfur hexafluoride	1	1	3	3	1	0	10	0%	99%	28,991	25,709	73,509	66,975	23,181	5,910	224,276	0.6%	98.9%
Pentafluoro(trifluoromethoxy)-ethane	2	1	3	1	1	0	8	0%	99%	19,298	10,784	29,517	10,139	5,747	4,844	80,329	0.2%	99.1%
Hexafluorooxetane	1	1	4	1	1	1	8	0%	99%	13,921	9,418	35,195	6,581	7,064	6,035	78,214	0.2%	99.4%
PFC-4-1-12 (Perfluoropentane)	2	1	1	1	2	1	8	0%	99%	18,958	8,201	9,053	5,933	15,605	13,627	71,377	0.2%	99.6%
Carbonyl fluoride	1	1	1	1	1	1	6	0%	99%	2,977	1,673	1,340	1,803	1,584	2,492	11,869	0.0%	99.6%
Trifluoroacetyl fluoride	1	1	1	1	1	1	5	0%	99%	2,493	1,654	1,339	1,638	1,651	1,890	10,664	0.0%	99.6%
HFC-43-10mee	1	1	1	1	0	1	5	0%	100%	1,657	1,504	1,673	1,163	0	1,529	7,526	0.0%	99.6%
Perfluoropropionyl fluoride	1	1	1	1	1	0	4	0%	100%	1,928	1,661	2,261	1,077	1,619	0	8,546	0.0%	99.7%
Perfluoro-2-(2-fluorosulfonylethoxy) propyl vinyl ether	0	0	0	0	1	3	4	0%	100%	0	0	0	0	2,167	5,654	7,821	0.0%	99.7%
2,2,3,3,4-Pentafluro-4-(trifluoromethyl)-oxetane	0	1	2	0	0	0	3	0%	100%	3,111	8,787	16,370	3,665	1,530	1,009	34,472	0.1%	99.8%
HFC-365mfc	0	0	3	0	0	0	3	0%	100%	0	0	2,620	0	0	0	2,620	0.0%	99.8%
PFC-6-1-12	1	1	0	0	0	0	3	0%	100%	8,867	10,099	1,078	1,110	2,219	0	23,373	0.1%	99.8%
Isobutyryl fluoride	2	0	0	0	0	0	2	0%	100%	4,668	0	0	0	0	0	4,668	0.0%	99.9%

TABLE 3A.1.2 (NEW) (CONTINUED)
ACTUAL EMISSIONS FROM PRODUCTION AND TRANSFORMATION PROCESS REPORTED BY SPECIFIC FLUORINATED GHG UNDER SUBPART L OF THE GHGRP (CONSIDERING CONTROLS) (APPROXIMATELY 98 PERCENT OF P/T PROCESS EMISSIONS IN METRIC TONNE CO_2 EQUIVALENT), METRIC TONNE AND METRIC TONNE CO_2 EQUIVALENT

Fluorinated GHG Name	2011	2012	2013	2014	2015	2016	Sum Total, tonne	% tonne	Cumulative %	2011	2012	2013	2014	2015	2016	Sum Total, tonne CO_2eq.	% tonne CO_2eq.	Cumulative %
1,1,1,3,3,5,5,7,7,9,9,11,11-tridecafluoro-2,4,6,8,10-pentaoxadodecan-12-oyl fluoride	0	0	0	0	1	0	1	0%	100%	0	0	0	0	2,993	0	2,993	0.0%	99.9%
HFC-227ca	0	0	1	0	0	0	1	0%	100%	0	1,120	2,727	0	0	0	3,846	0.0%	99.9%
2,3,3,3-Tetrafluoro-2-(trifluoromethoxy)propionyl fluoride	1	1	0	0	0	0	1	0%	100%	1,141	1,176	0	0	0	0	2,317	0.0%	99.9%
Heptafluoropropyl trifluoromethyl ether	0	0	0	0	0	0	1	0%	100%	1,299	1,004	3,103	0	1,143	2,086	8,635	0.0%	99.9%
2-Butene, 2-chloro-1,1,1,3,4,4,4-heptafluoro	1	0	0	0	0	0	1	0%	100%	1,380	0	0	0	0	0	1,380	0.0%	99.9%
Trifluoroacetic acid	0	0	1	0	0	0	1	0%	100%	0	0	1,378	0	0	0	1,378	0.0%	99.9%
1H-perfluorooctane	0	0	0	0	0	1	1	0%	100%	0	0	0	0	0	2,404	2,404	0.0%	99.9%
Unknown FC	0	0	0	0	0	0	1	0%	100%	0	0	0	0	2,267	3,888	6,155	0.0%	99.9%
[[Difluoro(trifluoromethoxy)methoxy]difluoromethoxy]difluoro-acetyl fluoride	0	0	0	0	0	1	1	0%	100%	0	0	0	0	0	1,190	1,190	0.0%	99.9%
Propanenitrile, 2,3,3,3-tetrafluoro-2-(trifluoromethyl)-	0	0	0	0	0	1	1	0%	100%	0	0	0	0	0	1,091	1,091	0.0%	99.9%
Unknown Sulfonated FC	0	0	0	0	0	0	1	0%	100%	0	0	3,143	1,036	0	1,238	5,417	0.0%	100.0%
Perfluoro compounds, C5-18	0	0	0	0	0	0	0	0%	100%	0	0	39	837	0	4,034	4,910	0.0%	100.0%
C5F13N	0	0	0	0	0	0	0	0%	100%	1,545	0	0	0	1,055	0	2,600	0.0%	100.0%
Perfluorotributyl amine	0	0	0	0	0	0	0	0%	100%	1,179	1,058	0	0	0	0	2,237	0.0%	100.0%
C6F15N	0	0	0	0	0	0	0	0%	100%	2,021	0	0	0	0	0	2,021	0.0%	100.0%
C7F16O	0	0	0	0	0	0	0	0%	100%	0	0	1,474	0	0	0	1,474	0.0%	100.0%
C6F12	0	0	0	0	0	0	0	0%	100%	0	0	0	0	1,015	0	1,015	0.0%	100.0%
Perfluorobutyliodide	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
HFC-1132a; VF2	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
HFC-1141; VF	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
1,1,1,3,3,3-Hexafluropropane	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%

Table 3A.1.2 (New) (Continued)
Actual emissions from production and transformation process reported by specific fluorinated GHG under Subpart L of the GHGRP (considering controls) (approximately 98 percent of P/T process emissions in metric tonne CO_2 equivalent), metric tonne and metric tonne CO_2 equivalent

Fluorinated GHG Name	2011	2012	2013	2014	2015	2016	Sum Total, tonne	% tonne	Cumulative %	2011	2012	2013	2014	2015	2016	Sum Total, tonne CO_2eq.	% tonne CO_2eq.	Cumulative %
1,2-Oxathiane, 3,3,4,4,5,5,6,6-octafluoro-, 2,2-dioxide	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
2,2,3,3,4,4,-hexafluoro-4-(fluorosufonyl)-butanoyl fluoride	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
2,3,3,3-Tetrafluoro-2-(heptafluoropropoxy)propanoyl fluoride	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
Heptafluoropropyl trifluorovinyl ether	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
Hexafluoroacetone	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
HFC-236ea	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
Methyl perfluoro(5-methyl-4,7-dioxanon-8-enoate)	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
Oxetane, 2,2,3,4,4-Pentafluro-3-(trifluoromethyl)-	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
Pentafluoroethyl trifluorovinyl ether	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
Perfluoroisobutyric acid fluoride	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
PFC-1114; TFE	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
PFC-1216; Dyneon HFP	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
PMVE; HFE-216	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
Propanoyl fluoride, 2,2,3,3-tetrafluoro-	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
1,2-Oxathiane, 3,3,4,4,5,5,6,6-octafluoro-, 2,2-dioxide	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
2,2,3,3,4,4,-hexafluoro-4-(fluorosufonyl)-butanoyl fluoride	-	-	-	-	-	-	-	0%	100%	-	-	-	-	-	-	-	-	100.0%
TOTAL	1,263	1,237	1,285	988	946	765	6,484			7,316,491	7,481,451	8,011,806	5,352,488	4,634,366	3,746,556	36,543,158		

[a] US EPA, 2017. Data extracted from US EPA Facility Level Information on Greenhouse Gases Tool (FLIGHT). Based on data reported to EPA by August 05, 2017 (freeze date). https://ghgdata.epa.gov/ghgp/main.do#

TABLE 3A.1.3 (NEW)
ACTUAL FLUORINATED GHG EMISSIONS FROM PRODUCTION AND TRANSFORMATION PROCESSES FROM SUBPART L OF THE GHGRP (CONSIDERING CONTROLS), BY GROUP (METRIC TONNE CO_2 EQUIVALENT) [A]

Fluorinated GHG Group	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Fully fluorinated GHGs	2,679,675	2,609,942	3,313,760	2,149,381	1,942,407	1,756,714
Saturated hydrofluorocarbons (HFCs) with 2 or fewer carbon-hydrogen bonds	4,068,950	4,350,171	4,065,235	2,684,590	2,198,462	1,380,406
Saturated HFCs with 3 or more carbon-hydrogen bonds	677,653	630,075	634,337	507,953	497,508	502,570
Saturated hydrofluoroethers (HFEs) and hydrochlorofluoroethers (HCFEs) with 1 carbon-hydrogen bond	3,324	3,358	25,048	42,617	42,781	97,454
Saturated HFEs and HCFEs with 2 carbon-hydrogen bonds	70	3	4	2	48	67
Saturated HFEs and HCFEs with 3 or more carbon-hydrogen bonds	3,741	4,130	4,743	3,777	4,124	5,289
Fluorinated formates	-	-	-	-	-	0
Fluorinated acetates, carbonofluoridates, and fluorinated alcohols other than fluorotelomer alcohols	62	17	93	243	120	126
Unsaturated perfluorocarbons (PFCs), unsaturated HFCs, unsaturated hydrochlorofluorocarbons (HCFCs), unsaturated halogenated ethers, unsaturated halogenated esters, fluorinated aldehydes, and fluorinated ketones	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis
Fluorotelomer alcohols	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis
Fluorinated GHGs with carbon-iodine bond(s)	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis
Other fluorinated GHGs	40,242	34,485	39,559	25,826	27,114	69,038
TOTAL	**7,473,716**	**7,632,181**	**8,082,779**	**5,414,389**	**4,712,564**	**3,811,664**

[a] Ibid EPA 2017.

We reviewed four DE assumptions, along with the uncontrolled emissions implied by these assumptions, to ensure that the default emission factor was as robust and accurate as possible.[16] These included:

1. A **lower-bound assumption** that assumed that the DE for each process was always equal to the lower bound of the DE range reported for that process. This results in an absolute lower-bound estimate of uncontrolled emissions. Uncontrolled emissions from any facility cannot fall below the level implied by this assumption.
2. An **upper-bound assumption** that assumed that the DE for each process was always equal to the upper bound of the DE range reported for that process. This results in an absolute upper-bound estimate of uncontrolled emissions.[17] Uncontrolled emissions from any facility cannot fall above the level implied by this assumption.
3. An **arithmetic mean assumption** that assumed that the DE for each process was equal to the straight average of the upper and lower bound of the DE range reported for that process. This is expected to be an unbiased estimator of uncontrolled emissions if a DE is equally likely to fall anywhere within the range and uncontrolled emissions are also equally likely to fall anywhere within the range (that is, uncontrolled emissions across processes and facilities are not expected to be higher at one end of the range than the other).
4. A **geometric mean assumption** that assumed that the DE for each process was equal to 1 minus the geometric mean of the fractions emitted at the DE range bounds reported for that process. (In Excel using MS Excel functions, this is summarized by the formula (1-GEOMEAN((1-LB),(1-UB)). This is expected to be an unbiased estimator of uncontrolled emissions if a DE is equally likely to fall anywhere within the range and uncontrolled emissions, across processes and facilities, grow exponentially as the DE increases.

The emissions prior to control for production and transformation processes are calculated using Equation 3A.1.1.

EQUATION 3A.1.1 (NEW)
EMISSIONS PRIOR TO CONTROL FOR PRODUCTION AND TRANSFORMATION PROCESSES

$$\textit{Emissions Prior to Control} = \left[\left(\textit{Post} - \textit{Control emissions from process vents}\right) \ / \ \left(1 - DE\right)\right] + \textit{Emissions from equipment leaks}$$

Table 3A.1.4 provides the estimated pre-abatement emissions by fluorinated GHG group (in metric tonne CO_2eq.) when each DE assumption is used to estimate pre-abatement emissions.

d. Selection of Arithmetic Mean as Basis for Estimates.

As the basis for our best estimates of uncontrolled emissions, we considered both the arithmetic and geometric means of the DE ranges. Choosing the appropriate DE assumption is based on the distribution of the emissions within each DE range. If the uncontrolled emissions are increasing exponentially across the range, then application of the geometric mean is more appropriate. If the uncontrolled emissions are constant across the range, then application of the arithmetic mean is more appropriate. Exponentially rising uncontrolled emissions would be consistent with a control strategy that selectively targeted the streams with the highest GWP-weighted emissions. It is clear that facilities tend to prioritize the control of high GWP streams and that this is often the first consideration in determining whether a stream will be controlled. In addition to high GWP, however, facilities also include other considerations in their decisions regarding which streams to send to a destruction device. Other considerations may include technical considerations, regulatory requirements, and safety concerns. Technical considerations include things such as the distance from the process to the destruction device for routing a vent to a control device, or the need to drop down the stream pressure prior to venting to a control device. Some facilities will have the technical expertise to overcome these issues while others may not. Another consideration is regulatory requirements or market forces that may affect whether a stream is controlled. In

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[16] As discussed in section A3.1.5 below, we also performed a Monte Carlo analysis to assess the uncertainty of the emission factor estimate, including the uncertainty of the exact DE as well as other uncertainties.

[17] This is unconditionally true for the first three DE ranges, but for the last one (>99 percent), we must choose a realistic upper bound because using a value of 100 percent would result in infinite pre-abatement emissions. We chose 99.99 percent, but we could have chosen 99.9 or 99.999 percent instead, with a factor of 10 difference either way for the pre-abatement emissions in this DE range. We also used the 99.99 percent upper bound to calculate the arithmetic and geometric means for the highest DE range.

addition, safety is a consideration. For example, there may be instances where the destruction device is down and not operating, and for safety reasons a process that is mid-process may be vented directly to the atmosphere.

Table 3A.1.4 provides the controlled emissions (actual) in metric CO_2eq., as well as the uncontrolled emissions in metric tonne CO_2eq. estimated using the lower bound of the DE range, the arithmetic mean of the DE range, the geometric mean of the DE range, and the upper bound of the DE range. These emissions include the full set of emissions from production and transformation processes. Note that the lower-bound uncontrolled emissions are approximately four times as large as the controlled emissions (though this varies by year). The estimates of uncontrolled emissions under the various DE assumptions span a factor of almost 30: the arithmetic-mean uncontrolled emissions are approximately twice as large as the lower-bound uncontrolled emissions, the geometric-mean uncontrolled emissions are approximately two and a half times as large as the arithmetic-mean uncontrolled emissions, and the upper-bound uncontrolled emissions are approximately seven times as large as the geometric-mean uncontrolled emissions.

Table 3A.1.4 (New)
Estimated pre-abatement fluorinated GHG emissions from production and transformation processes from Subpart L of the GHGRP, all DE assumptions (metric tonne CO_2 equivalent)

DE Assumption	2011	2012	2013	2014	2015	2016	Sum Total, tonne CO_2eq.
Actual emissions	7,473,716	7,632,181	8,082,779	5,414,389	4,712,564	3,811,664	37,127,293
Lower bound DE emissions, pre-abatement	33,126,816	26,348,042	22,970,419	23,678,050	21,459,616	27,852,452	155,435,395
Arithmetic mean DE emissions, pre-abatement	57,275,451	43,684,030	37,104,181	38,859,484	35,409,856	49,860,047	262,193,049
Geometric mean DE emissions, pre-abatement	162,302,698	89,923,131	60,355,569	73,690,456	70,568,769	167,408,713	624,249,337
Upper bound DE emissions, pre-abatement	1,275,608,396	541,882,779	256,555,587	400,139,115	407,755,113	1,441,071,577	4,323,012,567

One author compiled data on DEs achieved for one fluorochemical production process over several years, and these data showed a geometric distribution. However, there was no way to be certain that the distribution for this single process applied to the hundreds of other processes whose emissions are reported under subpart L. Thus, we selected the arithmetic mean, which assumes that uncontrolled emissions are flat as the DE increases, as the basis for our estimates of uncontrolled emissions. For this reason, the detailed analysis below focuses on the arithmetic mean scenario, but summary information is provided for the other scenarios to show the sensitivity of uncontrolled emissions to different DE assumptions. Table 3A.1.5 provides the uncontrolled emissions by fluorinated GHG group (in metric tonne CO_2eq.) estimated using the arithmetic mean of the DE range. The estimates in Table 3A.1.5 are used in section 3.1.4 to develop the profile of specific fluorinated GHGs emitted in a pre-abatement scenario.

TABLE 3A.1.5 (NEW)
ESTIMATED PRE-ABATEMENT FLUORINATED GHG EMISSIONS FROM PRODUCTION AND TRANSFORMATION PROCESSES FROM SUBPART L OF THE GHRP (USING ARITHMETIC MEAN OF DE RANGE), BY FLUORINATED GHG GROUP (METRIC TONNE CO_2 EQUIVALENT)

Fluorinated GHG Group	2011	2012	2013	2014	2015	2016
Fully fluorinated GHGs	42,739,622	29,929,077	23,858,516	27,730,456	24,770,670	39,481,096
Saturated hydrofluorocarbons (HFCs) with 2 or fewer carbon-hydrogen bonds	11,830,986	12,109,647	11,616,289	9,633,496	9,313,549	8,442,867
Saturated HFCs with 3 or more carbon-hydrogen bonds	2,436,833	1,452,855	1,426,863	1,257,906	1,073,521	1,340,253
Saturated hydrofluoroethers (HFEs) and hydrochlorofluoroethers (HCFEs) with 1 carbon-hydrogen bond	23,903	11,913	42,138	98,246	68,548	155,945
Saturated HFEs and HCFEs with 2 carbon-hydrogen bonds	384	555	792	376	319	471
Saturated HFEs and HCFEs with 3 or more carbon-hydrogen bonds	9,262	10,368	9,135	16,090	16,200	33,356
Fluorinated formats	-	-	-	-	-	0
Fluorinated acetates, carbonofluoridates, and fluorinated alcohols other than fluorotelomer alcohols	70	23	96	243	973	829
Unsaturated perfluorocarbons (PFCs), unsaturated HFCs, unsaturated hydrochlorofluorocarbons (HCFCs), unsaturated halogenated ethers, unsaturated halogenated esters, fluorinated aldehydes, and fluorinated ketones	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis
Fluorotelomer alcohols	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis
Fluorinated GHGs with carbon-iodine bond(s)	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis
Other fluorinated GHGs	234,391	169,593	150,352	122,671	166,076	405,231
TOTAL	**57,275,451**	**43,684,030**	**37,104,181**	**38,859,484**	**35,409,856**	**49,860,047**

3A.1.2.4 Container Venting Emissions

Container venting, or container evacuation, is another source of emissions that is common to fluorinated gas production facilities. Emissions from container venting occurred at 6 of the 16 facilities in the U.S. over RY2011 through RY2016. It is anticipated that all container venting emissions are uncontrolled, so no DE assumption is necessary. Table A3.1.6 provides actual GHG emissions for container venting in metric tonne CO_2eq., by individual facility. In later tables, container venting emissions have been included in the emission values along with the emissions from production and transformation processes.

TABLE 3A.1.6 (NEW)
ACTUAL EMISSIONS OF SPECIFIC FLUORINATED GHG FROM CONTAINER VENTING REPORTED UNDER SUBPART L OF THE GHGRP, BY FACILITY (METRIC TONNE AND METRIC TONNE CO_2 EQUIVALENT)

		Tonne						Tonne CO_2eq.					
Facility ID	**Facility name**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
526024	3M COMPANY	-	-	-	-	-	-	-	-	-	-	-	-
524391	3M CORDOVA	9	7	-	1	1	3	80,726	65,897	-	11,934	12,237	20,865
527519	3M Cottage Grove Center – Site	-	-	-	-	-	-	-	-	-	-	-	-
526434	ANDERSON DEVELOPMENT COMPANY	-	-	-	-	-	-	-	-	-	-	-	-
526676	ARKEMA, INC.	16	18	15	6	9	10	41,697	61,596	38,772	16,071	23,785	25,096
522460	Chemours - Corpus Christi Plant	-	-	-	-	-	-	-	-	-	-	-	-
523728	CHEMOURS CHAMBERS WORKS	-	-	-	-	-	-	-	-	-	-	-	-
523649	CHEMOURS COMPANY - FAYETTEVILLE WORKS	14	3	6	6	8	8	141,001	29,189	56,284	60,283	72,439	73,468
525649	Chemours EL DORADO	-	-	-	-	-	-	-	-	-	-	-	-
526198	Chemours LOUISVILLE WORKS	-	-	-	-	-	-	-	-	-	-	-	-
523005	Chemours WASHINGTON WORKS	-	-	-	-	-	-	-	-	-	-	-	-
527234	DAIKIN AMERICA INC.	-	-	-	-	-	-	-	-	-	-	-	-
522053	HONEYWELL INTERNATIONAL INC - BATON ROUGE PLANT	-	-	-	-	-	-	-	-	-	-	-	-
522051	HONEYWELL INTERNATIONAL INC - GEISMAR COMPLEX	-	-	-	-	1	-	-	-	-	-	1,494	-
522956	MEXICHEM FLUOR INC.	0	-	-	-	-	-	1	-	-	-	-	-
527776	Versum Materials US, LLC	-	-	-	-	1	-	-	-	-	-	5 ,081	-
	TOTAL	**39**	**28**	**21**	**14**	**20**	**20**	**263,425**	**156,683**	**95,056**	**88,287**	**115,036**	**119,429**

3A.1.2.5 Production and Transformation Quantities Reported Under Subpart OO, Suppliers of Greenhouse Gases

Facilities that produce and transform fluorinated GHGs report the production and transformation quantities to the GHGRP under subpart OO. These data are considered confidential business information on an individual facility basis, and are therefore not publicly available. Table A3.1.7 provides total aggregate fluorinated GHG data on a metric tonne basis for production and transformation processes for subpart OO.

TABLE 3A.1.7 (NEW)
PRODUCTION AND TRANSFORMATION QUANTITIES REPORTED UNDER SUBPART OO OF THE GHGRP (METRIC TONNE)

Quantity	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Production and Transformation of Fluorinated Gas	291,000	276,000	302,000	307,000	278,000	315,000

3A.1.3EMISSION FACTOR DEVELOPMENT FOR FLUORINATED GHGS

3A.1.3.1 Estimated pre-abatement emission in metric tonne for Average Emissions Factor Analysis

The average emission factor was developed in terms of metric tonne of emissions. To support this analysis, calculations that estimate the pre-abatement emissions of fluorinated GHG on a metric ton basis must be performed.

The calculations that result in the emissions shown in Table 3A.1.5 above yield GWP-weighted, estimated pre-abatement emissions in metric tonne of CO_2eq. for each production or transformation process. To estimate emissions in metric tonne prior to control, we need a way to estimate the weighted average GWP for each facility and reporting year, to account for the fact that fluorinated GHGs with different GWPs may be controlled at different levels. That is, the GWP distribution of actual emissions may not match the GWP distribution of pre-abatement emissions. We can then divide the emissions in metric tonne of CO_2eq. by the corresponding GWP to calculate the emissions in metric tons. (Recall that the US EPA receives DE range information on a process basis, but does not receive data on individual fluorinated GHGs by process.) The steps we followed to derive the GWPs are outlined below.

a. Weighted-average GWP of controlled emissions. We first calculated the weighted-average GWP of the controlled emissions for each facility and year by dividing (1) the total actual emissions reported by each facility for all production and transformation processes in metric tonne of CO_2eq. by (2) the emissions calculated for each facility in metric tons.[18] However, we cannot necessarily apply this weighted average GWP to the estimated pre-abatement emissions calculated for that facility and year. Because facilities may control emissions with different GWPs to varying extents, the average GWP of the pre-abatement emissions may be different from the average GWP of the actual emissions.

b. Factor to Calculate Weighted-average GWP for Estimated Pre-abatement Emissions. To account for different control levels that may be applied to fluorinated GHGs having different GWPs, we used the process-level reporting of actual emissions by fluorinated GHG group in metric tonne of CO_2eq., as well as our calculations of pre-abatement emissions based on these numbers. Where processes that emit higher-GWP fluorinated GHG groups are controlled to a greater extent than processes that emit lower-GWP fluorinated GHG groups, the calculated emissions of the former will grow more than the calculated emissions of the latter as one moves from the controlled to the pre-abatement scenario. This signal appears in the pre-abatement emissions calculated under the DE assumption in section A3.1.2.3.c above. We can use this signal, along with assumptions about the average GWP of each fluorinated GHG group, to estimate how the weighted-average GWP has changed from the controlled scenario. Using this approach, we developed a ratio of the weighted-average GWP of the estimated pre-abatement emissions to the weighted-average GWP of the actual emissions for each facility and reporting year, and multiplied this ratio by the GWP of the controlled emissions calculated in Step a. Specifically, we performed the following calculations:

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[18] Emissions in metric tonne are calculated as the sum of the emissions that are reported by specific fluorinated GHG in metric tonne (reported in metric tonne of fluorinated GHG), plus the estimated emissions of fluorinated GHGs whose emissions are reported by fluorinated GHG group in metric tonne CO_2eq., after conversion to metric tonne. For the latter, the GWP-weighted emissions are divided by the average GWP for each group to calculate emissions in metric tonne.

1. For each facility and reporting year, we assumed that the emissions of each fluorinated GHG group had the average GWP of that group and divided the metric tonne of CO_2eq. emissions for that group by the weighted-average GWP to obtain estimates of emissions in metric tonne. We then totaled both metric tonne CO_2eq. and metric tonne for all groups, and divided the first by the second to get a weighted-average GWP (uncontrolled) for that facility and year.
2. Then we divided the weighted-average GWP (pre-abatement) for each facility and reporting year by the GWP for the actual controlled scenario for that facility and year to obtain a set of ratios.
3. Finally, we multiplied these ratios by the weighted-average GWPs (for each facility and year) that we calculated for the controlled (actual) scenario in Step a.

The estimated pre-abatement fluorinated GHG emissions, in metric tonne, for production and transformation processes based on the adjusted GWP are provided for the arithmetic mean DE assumption, by individual facility in Table 3A.1.8.

TABLE 3A.1.8 (NEW)
ESTIMATED PRE-ABATEMENT FLUORINATED GHG EMISSIONS FROM PRODUCTION AND TRANSFORMATION PROCESSES PLUS CONTAINER VENTING FROM SUBPART L OF THE GHGRP (USING ARITHMETIC MEAN OF DE RANGE) BY FACILITY (METRIC TONNE)

FACILITY NAME	2011	2012	2013	2014	2015	2016
3M COMPANY	2	4	5	6	2	3
3M CORDOVA	4,348	3,219	2,493	3,005	2,730	4,442
3M Cottage Grove Center – Site	5	7	8	3	3	3
ANDERSON DEVELOPMENT COMPANY	9	9	4			
ARKEMA, INC.	1,018	1,385	1,232	1,075	1,198	1,411
Chemours - Corpus Christi Plant	27	40	35	13	9	35
CHEMOURS CHAMBERS WORKS	75	82	102	73	62	34
CHEMOURS COMPANY - FAYETTEVILLE WORKS	76	68	71	72	109	119
Chemours EL DORADO	22	21	22	22	25	21
Chemours LOUISVILLE WORKS	19	9	12	10		
Chemours WASHINGTON WORKS	297	57	34	29	65	386
DAIKIN AMERICA INC.	44	37	39	44	46	49
HONEYWELL INTERNATIONAL INC - BATON ROUGE PLANT	70	76	78	50	55	41
HONEYWELL INTERNATIONAL INC - GEISMAR COMPLEX	2,547	1,119	1,247	1,243	1,298	430
MEXICHEM FLUOR INC.	42	42	7	7	10	9
Versum Materials US, LLC	39	38	27	26	29	26
TOTAL	**8,638**	**6,211**	**5,415**	**5,680**	**5,641**	**7,009**

3A.1.3.2 Metric of the Emission Factor

The goal of our analysis was to develop an emission factor in terms of metric tonne of fluorinated GHG emissions divided by metric tonne of fluorinated gas produced and transformed (Total emissions in metric tonne / production and transformation quantity produced, in metric tonne). This is because any GWPs or other metrics used to express fluorinated gas emissions relative to CO_2 may go out of date after publication of the emission factor, potentially reducing the applicability of the factor.[19]

We developed an unweighted average EF (i.e., average across facilities of each facility's emission factor, where that factor equals the facility's emissions divided by the sum of that facility's production and transformation). We also examined the standard deviation of the facility-specific emission factors. For an average, each facility is weighted equally and facilities with comparatively larger or smaller EF values influence the average value even if the quantities that they produce and/or transform are small. The average emission factor, based on an average, was calculated to be 0.04 metric tonne fluorinated GHG emissions per metric tonne quantity produced and transformed.

TABLE 3A.1.9 (NEW)
DEFAULT EMISSION FACTOR FOR FLUORINATED PRODUCTION

	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**Average Across Years**
EF based on Arithmetic Mean, metric tonne/ metric tonne	0.05	0.04	0.03	0.04	0.03	0.04	0.04
Standard Deviation	0.1	0.1	0.07	0.1	0.08	0.1	
Relative Standard Deviation	200%	250%	230%	250%	270%	250%	
95% confidence interval	390%	490%	450%	490%	520%	490%	470%

3A.1.4ANALYSIS OF COMMON FLUORINATED GHGS EMITTED FROM FLUOROCHEMICAL PROCESSES

The emission factor in Table A3.1.9 is expressed in terms of metric tonne emitted per metric tonne produced or transformed. To be of use for an emissions inventory, knowledge of, or assumptions regarding, the fluorinated GHGs emitted is necessary. This section summarizes the data and approach used for identifying the most emitted fluorinated GHGs from fluorochemical production based on the data reported by facilities to the U.S. GHGRP.

3A.1.4.1 Develop Ratios for Most Emitted Fluorinated GHG Emissions Analysis

To identify the most emitted fluorinated GHGs, the analysis begins with comparing the actual emissions by fluorinated GHG group (summarized in Table A3.1.3) with the estimated pre-abatement emissions (the estimated pre-abatement emissions are shown in Table A3.1.5). The DE range is provided for each production and transformation process but is not provided for individual specific fluorinated GHGs. To calculate these pre-abatement emissions, we need a way to estimate the unweighted metric tonne for each fluorinated GHG group and reporting year. The calculations in Table A3.1.5 yield GWP-weighted, pre-abatement emissions in metric tonne CO_2eq. for each production or transformation process. A ratio of the pre-abatement emissions in metric tonne CO_2eq. compared to the actual emissions in metric tonne CO_2eq. can be developed for each fluorinated GHG group and reporting year. These ratios can then be applied to the actual emissions of specific fluorinated GHG in metric tonne CO_2eq. to appropriately estimate the pre-abatement level of specific fluorinated GHG in metric tonne. (Recall that the US EPA does not receive data on unweighted emissions, metric tonne, of individual fluorinated GHGs by process.) The ratios of pre-abatement metric tonne CO_2eq. compared to actual metric tonne CO_2eq. are provided in Table A3.1.10.

A3.1.4.2 Pre-abatement Emissions in metric tonne CO_2eq. and metric tonne for Specific Fluorinated GHGs, for Production and Transformation Processes, and Container Venting

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[19] We also reviewed factors using GWP-weighted emissions and production/transformation quantities because they provided insight into how the GWPs of fluorinated GHGs emitted relate to the GWPs of fluorinated gases produced across facilities.

Applying the ratios in Table A3.1.10 to the Table A3.1.2 actual emissions provides the pre-abatement emissions by fluorinated GHG (in metric tonne CO_2eq.). The ratios were multiplied by the specific fluorinated GHG, based on its fluorinated GHG group, for each reporting year. The estimated pre-abatement emissions by specific fluorinated GHG, in metric tonne CO_2eq. and metric tonne, are provided in Table A3.1.11 for production and transformation processes, along with the container venting emissions.

A3.1.4.3 Representative Fluorinated GHG Profile

The most commonly emitted fluorinated GHGs on a pre-abatement emissions basis can be determined from the data set. The most common fluorinated GHGs, by metric tonne and by metric tonne CO_2eq., are shown in Table A3.1.12. Those fluorinated GHGs that do not have GWPs in any IPCC Assessment Report (e.g., the Fifth Assessment Report) have been dropped from the list (i.e., hexafluoropropylene oxide, and octafluorotetrahydrofuran). The analysis shows the representative chemical composition in metric tonne for the top 10 fluorinated GHGs.

TABLE 3A.1.10 (NEW)
RATIOS OF ESTIMATED PRE-ABATEMENT EMISSIONS IN METRIC TONNE CO_2 EQUIVALENT (USING ARITHMETIC MEAN OF DE RANGE) TO ACTUAL EMISSIONS IN METRIC TONNE OF CO_2 EQUIVALENT

Fluorinated GHG Group	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Fully fluorinated GHGs	15.9	11.5	7.2	12.9	12.8	22.5
Saturated hydrofluorocarbons (HFCs) with 2 or fewer carbon-hydrogen bonds	2.9	2.8	2.9	3.6	4.2	6.1
Saturated HFCs with 3 or more carbon-hydrogen bonds	3.6	2.3	2.2	2.5	2.2	2.7
Saturated hydrofluoroethers (HFEs) and hydrochlorofluoroethers (HCFEs) with 1 carbon-hydrogen bond	7.2	3.5	1.7	2.3	1.6	1.6
Saturated HFEs and HCFEs with 2 carbon-hydrogen bonds	5.5	191.2	193.2	198.0	6.7	7.0
Saturated HFEs and HCFEs with 3 or more carbon-hydrogen bonds	2.5	2.5	1.9	4.3	3.9	6.3
Fluorinated formats						1.6
Fluorinated acetates, carbonofluoridates, and fluorinated alcohols other than fluorotelomer alcohols	1.1	1.4	1.0	1.0	8.1	6.6
Unsaturated perfluorocarbons (PFCs), unsaturated HFCs, unsaturated hydrochlorofluorocarbons (HCFCs), unsaturated halogenated ethers, unsaturated halogenated esters, fluorinated aldehydes, and fluorinated ketones	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis
Fluorotelomer alcohols	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis
Fluorinated GHGs with carbon-iodine bond(s)	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis	Excluded from analysis
Other fluorinated GHGs	5.8	4.9	3.8	4.7	6.1	5.9

Table 3A.1.11 (New)
Estimated pre-abatement fluorinated GHG emissions from production processes, transformation processes, and container venting from Subpart L of the GHGRP (using arithmetic mean of DE range), by specific fluorinated GHG (metric tonne CO_2 equivalent and metric tonne)

Fluorinated GHG Name	2011	2012	2013	2014	2015	2016	Sum Total, tonne	2011	2012	2013	2014	2015	2016	Sum Total, tonne CO_2eq.
PFC-14 (Perfluoromethane)	961	882	417	605	581	1,224	4,670	7,099,740	6,517,927	3,082,715	4,471,865	4,293,330	9,047,657	34,513,233
HFC-134a	780	621	599	731	963	904	4,598	1,115,275	888,437	857,188	1,045,203	1,377,357	1,292,344	6,575,805
Perfluorocyclobutane	846	404	188	372	359	1,169	3,338	8,717,609	4,161,124	1,932,044	3,829,822	3,700,681	12,038,028	34,379,308
HFC-32	452	459	436	418	551	556	2,872	305,085	309,916	294,328	281,876	371,685	375,472	1,938,362
HFC-125	447	428	450	543	579	387	2,834	1,565,149	1,496,910	1,574,237	1,901,966	2,025,422	1,355,484	9,919,168
HFC-23	556	596	567	403	341	322	2,784	8,227,363	8,814,039	8,386,194	5,960,713	5,047,891	4,763,628	41,199,828
HFC-143a	492	299	290	249	201	274	1,805	2,199,566	1,337,071	1,295,696	1,111,496	899,663	1,223,588	8,067,080
Nitrogen trifluoride	493	322	141	204	194	286	1,639	8,472,427	5,534,029	2,420,335	3,510,222	3,331,771	4,921,716	28,190,500
Hexafluoropropylene oxide	197	201	143	260	305	411	1,517	1,969,139	2,005,481	1,427,557	2,604,466	3,054,522	4,109,247	15,170,411
PFC-116 (Perfluoroethane)	327	232	287	219	297	40	1,402	3,991,281	2,827,549	3,498,551	2,674,161	3,625,619	484,819	17,101,979
Octafluorotetrahydrofuran	301	290	285	299	72	108	1,355	3,005,532	2,901,350	2,848,074	2,993,494	715,725	1,084,733	13,548,907
Pentafluoro(trifluoromethyl)-cyclopropane	164	95	74	145	245	343	1,065	1,640,970	945,229	743,174	1,445,947	2,449,359	3,429,930	10,654,610
PFC-218 (Perfluoropropane)	202	89	346	211	42	63	953	1,785,524	783,260	3,058,038	1,859,967	373,114	557,703	8,417,605
PFC-5-1-14 (Perfluorohexane, FC 72)	187	94	57	132	162	135	769	1,741,556	877,250	532,641	1,227,637	1,508,328	1,260,091	7,147,504
HFC-245fa	173	112	109	124	90	110	718	178,341	115,212	112,576	127,561	93,150	112,998	739,839
HFC-227ea	76	70	100	85	108	138	578	245,039	226,497	321,319	274,773	347,144	444,859	1,859,631
Trifluoromethyl sulphur pentafluoride	123	108	135	67	34	38	505	2,176,556	1,906,677	2,394,848	1,187,441	607,481	668,577	8,941,579
HFE-449sl, (HFE-7100) Isomer blend	27	28	23	39	34	68	219	7,899	8,194	6,890	11,646	10,205	20,154	64,987
PFC-3-1-10 (Perfluorobutane)	32	17	44	34	13	48	188	284,753	153,082	392,867	296,961	116,592	422,942	1,667,196
Perfluorodiethyl ether	27	34	15	18	21	36	151	267,613	337,690	154,228	175,707	209,907	364,894	1,510,039
HFC-152a	32	21	27	0	0	57	137	3,915	2,656	3,355	0	0	7,023	16,949
PFC-4-1-12 (Perfluoropentane)	33	10	7	8	22	33	114	302,372	94,043	65,179	76,544	199,003	306,266	1,043,407
Sulphur hexafluoride	20	13	23	38	13	6	113	462,400	294,817	529,256	864,085	295,614	132,818	2,578,990
2H-perfluoro(5-methyl-3,6-dioxanonane)	23	22	12	8	14	32	111	45,291	44,616	23,279	16,442	28,198	64,653	222,479

Table 3A.1.11 (New) (Continued)
Estimated pre-abatement fluorinated GHG emissions from production processes, transformation processes, and container venting from Subpart L of the GHGRP (using arithmetic mean of DE range), by specific fluorinated GHG (metric tonne and metric tonne CO_2 equivalent)

Fluorinated GHG Name	2011	2012	2013	2014	2015	2016	Sum Total, tonne	2011	2012	2013	2014	2015	2016	Sum Total, tonne CO_2eq.
Trifluoromethanesulfonyl fluoride	19	21	23	18	10	8	99	38,164	41,308	46,446	35,632	19,053	16,439	197,043
Pentafluoro(trifluoromethoxy)-ethane	31	12	21	13	7	11	96	307,788	123,664	212,517	130,809	73,289	108,866	956,934
Hexafluorooxetane	22	11	25	8	9	14	89	222,031	107,999	253,398	84,905	90,084	135,633	894,051
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	3	2	6	15	10	24	61	21,710	11,216	41,875	98,125	67,150	155,716	395,791
Perfluorobutanesulfonyl fluoride	7	4	4	4	8	30	57	14,158	8,234	7,949	8,739	16,279	59,609	114,969
HFC-236fa	7	9	14	10	8	9	57	64,409	92,657	136,907	102,260	76,647	90,648	563,528
PFC-6-1-12	18	15	1	2	4	0	39	141,418	115,806	7,764	14,326	28,302	0	307,616
2,2,3,3,4-Pentafluoro-4-(trifluoromethyl)-oxetane	5	10	12	5	2	2	36	49,625	100,763	117,861	47,284	19,511	22,941	357,986
Carbonyl fluoride	9	4	3	4	5	7	32	17,338	8,230	5,092	8,564	9,703	14,629	63,556
Trifluoroacetyl Fluoride	7	4	3	4	5	6	28	14,520	8,132	5,089	7,778	10,115	11,091	56,727
Perfluoro-2-(2-Fluorosulfonylethoxy) Propyl Vinyl Ether	0	0	0	0	7	17	23	0	0	0	0	13,276	33,186	46,462
Perfluoropropionyl fluoride	6	4	4	3	5	0	22	11,228	8,170	8,592	5,117	9,915	0	43,022
HFC-43-10mee	3	3	3	3	0	6	17	4,819	4,186	4,780	4,172	0	9,354	27,311
isobutyryl fluoride	14	0	0	0	0	0	14	27,191	0	0	0	0	0	27,191
Unknown FC	0	0	0	0	3	9	12	0	0	0	0	28,910	87,380	116,291
Heptafluoropropyl Trifluoromethyl Ether	2	1	2	0	1	5	12	20,717	11,513	22,341	0	14,576	46,882	116,029
Perfluro compounds, C5-18	0	0	0	1	0	9	10	0	0	281	10,799	0	90,662	101,741
1,1,1,3,3,5,5,7,7,9,9,11,11-tridecafluoro-2,4,6,8,10-pentaoxadodecan-12-oyl fluoride	0	0	0	0	9	0	9	0	0	0	0	18,330	0	18,330
HFC-365mfc	0	0	7	0	0	0	7	0	0	5,894	0	0	0	5,894
Unknown Sulfonated FC	0	0	2	1	0	3	6	0	0	22,629	13,366	0	27,823	63,818
2,3,3,3-Tetrafluoro-2-(trifluoromethoxy)propionyl fluoride	3	3	0	0	0	0	6	6,643	5,785	0	0	0	0	12,429
HFC-227ca	0	1	3	0	0	0	4	0	3,117	7,792	0	0	12	10,921
2-Butene, 2-chloro-1,1,1,3,4,4,4-heptafluoro	4	0	0	0	0	0	4	8,038	0	0	0	0	0	8,038

Table 3A.1.11 (New) (Continued)
Estimated pre-abatement fluorinated GHG emissions from production processes, transformation processes, and container venting from Subpart L of the GHGRP (using arithmetic mean of DE range), by specific fluorinated GHG (metric tonne and metric tonne CO_2 equivalent)

Fluorinated GHG Name	2011	2012	2013	2014	2015	2016	Sum Total, tonne	2011	2012	2013	2014	2015	2016	Sum Total, tonne CO_2eq.
1H-perfluorooctane	0	0	0	0	0	4	4	0	0	0	0	0	14,703	14,703
C5F13N	2	0	0	0	1	0	4	24,634	0	0	0	13,454	0	38,088
[[Difluoro(trifluoromethoxy)methoxy] difluoromethoxy] difluoro-acetyl fluoride	0	0	0	0	0	3	3	0	0	0	0	0	6,987	6,987
C6F15N	3	0	0	0	0	0	3	32,227	0	0	0	0	0	32,227
Propanenitrile, 2,3,3,3-tetrafluoro-2-(trifluoromethyl)-	0	0	0	0	0	3	3	0	0	0	0	0	6,406	6,406
Perfluorotributyl amine	2	1	0	0	0	0	3	18,802	12,132	0	0	0	0	30,934
Trifluoroacetic Acid	0	0	3	0	0	0	3	0	0	5,239	0	0	0	5,239
C6F12	0	0	0	0	1	0	1	0	0	0	0	12,944	0	12,944
C7F16O	0	0	1	0	0	0	1	0	0	10,613	0	0	0	10,613
2,3,3,3-Tetrafluoro-2-(heptafluoropropoxy)propanoyl fluoride	0	0	0	0	0	0	1	0	0	0	0	741	466	1,207
Perfluroisobutyric acid fluoride	0	0	0	0	0	0	0	0	0	0	0	0	442	442
1,1,1,3,3,3-hexafluoropropane	0	0	0	0	0	0	0	0	0	0	0	0	91	91
2,2,3,3,4,4,-hexafluoro-4-(fluorosufonyl)-butanoyl fluoride	0	0	0	0	0	0	0	0	0	0	0	0	39	39
Oxetane, 2,2,3,4,4-Pentafluoro-3-(trifluoromethyl)-	0	0	0	0	0	0	0	0	0	0	0	0	156	156
1,2-Oxathiane, 3,3,4,4,5,5,6,6-octafluoro-, 2,2-dioxide	0	0	0	0	0	0	0	0	0	0	0	0	6	6
Propanoyl fluoride, 2,2,3,3-tetrafluoro-	0	0	0	0	0	0	0	0	0	0	0	0	5	5
HFC-236ea	0	0	0	0	0	0	0	0	0	0	0	0	3	3
TOTAL	**7,137**	**5,551**	**4,914**	**5,303**	**5,338**	**6,958**	**35,202**	**56,855,857**	**43,245,968**	**36,877,626**	**38,521,874**	**35,204,040**	**49,429,797**	**260,135,162**

TABLE 3A.1.12 (NEW)
TOP-10 EMITTED SPECIFIC FLUORINATED GHG, FROM PRODUCTION PROCESSES, TRANSFORMATION PROCESSES, AND CONTAINER VENTING FROM SUBPART L OF THE GHGRP (USING ARITHMETIC MEAN OF DE RANGE ENDPOINTS)[A]

Fluorinated GHG Name	Sum total, tonne	Percent	GHG Group
PFC-14 (Perfluoromethane)	4,670	18%	Fully fluorinated GHGs
HFC-134a	4,598	18%	Saturated HFCs with 2 or fewer carbon-hydrogen bonds
Perfluorocyclobutane	3,338	13%	Fully fluorinated GHGs
HFC-32	2,872	11%	Saturated HFCs with 2 or fewer carbon-hydrogen bonds
HFC-125	2,834	11%	Saturated HFCs with 2 or fewer carbon-hydrogen bonds
HFC-23	2,784	11%	Saturated HFCs with 2 or fewer carbon-hydrogen bonds
HFC-143a	1,805	7%	Saturated HFCs with 3 or more carbon-hydrogen bonds
Nitrogen trifluoride	a	a	Fully fluorinated GHGs
Hexafluoropropylene oxide	b	b	Fully fluorinated GHGs
PFC-116 (Perfluoroethane)	1,402	5%	Fully fluorinated GHGs
Octafluorotetrahydrofuran	b	b	Fully fluorinated GHGs
Pentafluoro(trifluoromethyl)-cyclopropane	b	b	Fully fluorinated GHGs
PFC-218 (Perfluoropropane)	953	4%	Fully fluorinated GHGs
PFC-5-1-14 (Perfluorohexane, FC 72)	769	3%	Fully fluorinated GHGs

Due to rounding, the sum of individual items will not equal 100%.

[a] The *2019 Refinement* includes separate emission factors specifically for NF_3 production. As approximately 92 percent of NF_3 emissions are from intended NF_3 production, and NF_3 is not commonly emitted from the production of other fluorochemicals, NF_3 has been dropped from the analysis for representative composition.

[b] These fluorinated GHGs that do not have GWPs in any IPCC Assessment Report (e.g., the Fifth Assessment Report) have been dropped from the analysis for representative composition.

3A.1.5 UNCERTAINTY ANALYSIS OF AVERAGE EMISSION FACTOR

In addition to examining the sensitivity of calculated uncontrolled (i.e., pre-abatement) emissions to various assumptions regarding the DE, we performed a Monte Carlo analysis to comprehensively assess the uncertainty of the emission factor, given the uncertainty of the DE as well as other sources of uncertainty. The uncertainty in the estimated pre-abatement emission in units of metric tonne CO_2eq. is based on the wide ranges of the DE. The uncertainty in the pre-abatement emission estimates in terms of metric tonne of fluorinated GHG is based on the combination of the uncertainty in the DE and the uncertainty in the average GWP of the specific fluorinated GHGs in the pre-abatement scenario. With respect to the DEs, we used the following assumed distribution.

TABLE 3A.1.13 (NEW)
DISTRIBUTION ASSUMPTIONS FOR THE DE RANGES

DE ranges	Distribution Assumptions
≥0% to <75%	Half of the values are 0%; half of the values flat distribution between 0 and 74.9%
≥75% to <95%	Flat distribution between 75 and 94.9%
≥95% to <99%	Flat distribution between 95 and 98.9%
≥99%	Triangular distribution between 99 and 99.99% with mode at 99%

Because we expected that a significant number of reporters using the ≥0 to <75 percent range were uncontrolled, we assumed a distribution function that assigns half of the distribution function to 0 percent DE.

For estimating the uncertainty in the GWP, we evaluated the data for emissions by specific fluorinated GHG compound (in metric tonne of specific GHG) that was reported for the facility as a whole. We developed different GWP distributions for each facility and fluorinated GHG group combination based on the data reported for a given facility. If only one specific fluorinated GHG compound was reported for a given facility within a fluorinated GHG group (or if all of the specific GHGs reported by the facility were identical), the GWP of that compound was used directly (no uncertainty). If multiple specific fluorinated GHG compounds with different GWPs were reported within a fluorinated GHG group for a given facility, we calculated the weighted average GWP for that group based on the specific fluorinated GHG's GWP and direct mass emissions reported by that facility. The weighted average GWP across all reporting years was used as the central tendency value and the weighted average for individual years was used to assess the range of the distribution function for the uncertainty analysis. In some cases, the emissions for specific fluorinated GHG compounds in a group did not exceed the separate reporting threshold (1,000 metric tonne CO_2eq.) of subpart L, and only the metric tonne CO_2eq. emissions for the fluorinated GHG group were reported at the facility level. In this case, the individual GWPs for all compounds listed within that fluorinated GHG group was used as the distribution function, and a random GWP was selected from those values. When we first utilized this approach, the very low-GWP fluorinated GHG groups (i.e., those groups whose members had GWPs near or below 1) dominated the estimated pre-abatement fluorinated GHG emissions (in direct mass terms), which led to huge uncertainties in the mass emission rates for compounds that had a negligible impact on emissions in terms of CO_2eq. Consequently, we excluded the very-low-GWP fluorinated GHG groups' emissions when estimating the mass of fluorinated GHG compound emissions for developing the proposed emissions factor. For similar reasons, we used a lower GWP of 0.5 for the fluorinated acetates, carbonofluoridates, and fluorinated alcohols other than fluorotelomer alcohols group, rather than 0.05 value for 4,4,4-trifluorbutan-1-ol (CAS No. 461-18-7). It was assumed that, even if this compound was the primary pollutant emitted from this group, small amounts of other compounds from this group would also likely be emitted and that the value of 0.5 was a reasonable lower bound for this group.

Calculations of the pre-abatement emissions (in both metric tonne CO_2eq. and in metric tonne of fluorinated GHG group) were made using the process level emissions reported under subpart L. A Monte Carlo analysis using 10,000 random realizations was used to estimate the average and 95th percentile confidence intervals for the emissions. We assumed the uncertainty in the reported production quantities were negligible relative to the uncertainties in the uncontrolled emissions.

The average annual estimated pre-abatement emissions in metric tonne CO_2eq. from the Monte Carlo analysis compares reasonably well with but are slightly lower than the pre-abatement emissions estimates using the arithmetic mean DE assumption for the range. This is because the lowest and highest DE ranges were skewed towards the lower DE values in the Monte Carlo analysis. The total estimated pre-abatement emissions in metric tonne of fluorinated GHG compounds from the Monte Carlo analysis (when excluding the low GWP groups) had similar uncertainty ranges as the total estimated pre-abatement emissions in CO_2e (which are based only on uncertainty of the DE) for most facilities. A few facilities that had reported generic emissions of the fluorinated acetates, carbonofluoridates, and fluorinated alcohols other than fluorotelomer alcohols group had much higher uncertainty in their mass emissions than in their CO_2e emissions due to the variability and uncertainty associated with the GWP.

The uncertainty in the average emission factor across all of the reporting facilities (i.e., the 95-percent confidence interval around the sample mean), including the uncertainties in both the DE and in the GWP of the emitted gases, was 20 percent. In summary, these sources of uncertainty are mitigated by the large number of data points in the analysis, which come from the large number of processes and significant number of years covered. Thus, the errors related to the DE estimated for each individual process and to the mix of gases emitted tend to balance out, and the aggregate uncertainty is reduced.

It is important to note that the uncertainty in the emission factor for any single facility is much larger than this, and is dictated by the fact that true pre-abatement emission rates naturally vary from facility to facility depending on the fluorochemicals produced and the processes used to make them. This variability appears in the U.S. EPA data as differences in the estimated pre-abatement emission factors across facilities, differences that persist over the entire time series. The year-to-year variability seen in the estimated pre-abatement emission factor for any one facility is generally much smaller than this facility-to-facility variability. The uncertainty shown in Table 3A.1.9 reflects this variation among facilities. The 95 percent confidence interval (calculated based on the relative standard deviation among the facilities' emission factors) is ±470 percent. Because there cannot be a negative emission factor on the low side, a value of 0.001 was selected as the lower uncertainty bound, as it is representative of lower emission factor values seen in the data set. This results in an uncertainty range for the Tier 1 default emission factor of 0.001 to 0.2.

As noted in section 3A.1.2 above, the selected EF is based on the straight average analysis. The average EF based on the straight average is similar to the EF based on the Monte Carlo analysis. The overall EF that results from other assumptions, such as use of a weighted average or use of the geometric mean, are also provided in Table 3A.1.14 to provide additional context.

TABLE 3A.1.14 (NEW)
COMPARISON OF EMISSION FACTOR VALUES IN PARALLEL ANALYSES

Selected EF	**EF value, metric tonne/metric tonne**
Arithmetic Mean DE assumption, straight average	**0.04**
Other EF Bases	
Arithmetic Mean DE assumption, weighted average	0.02
Geometric Mean DE assumption, weighted average	0.05
Monte Carlo	0.04

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CHAPTER 4

METAL INDUSTRY EMISSIONS

Authors

Section 4.2

Laura E. Dawidowski (Argentina), Oleksandra Kolmogortseva (Ukraine), Ingrid Person Rocha e Pinho (Brazil) and Teruo Okazaki (Japan)

Section 4.4

Lukas Dion (Canada), Pernelle Nunez (IAI/UK), Alexey V. Spirin (Russian Federation) and David Sydney Wong (New Zealand)

Section 4.8

David Sydney Wong (New Zealand), Lukas Dion (Canada), Pernelle Nunez (IAI/UK) and Alexey V. Spirin (Russian Federation).

Contributing Authors

Section 4.2

Jan Hendrik Reimink (WSA/Netherlands)

Section 4.4

Simon Gaboury (Canada), Jerry Y. Marks (USA), Andrey V. Panov (Russian Federation), Xin Bo (China) and Xiping Chen (China).

Section 4.8

Michalopoulou Eleni (UK), Hanno Vogel (Germany), Youming Yang (China), Xin Bo (China) and Xiping Chen (China).

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4 METAL INDUSTRY EMISSIONS

Users are expected to go to Mapping Tables in Annex 5, before reading this chapter. This is required to correctly understand both the refinements made and how the elements in this chapter relate to the corresponding chapter in the 2006 IPCC Guidelines.

4.1 INTRODUCTION

No refinement.

4.2 IRON & STEEL AND METALLURGICAL COKE PRODUCTION

The production of iron and steel leads to emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). This chapter provides guidance for estimating emissions of CO_2 and CH_4.[1]

The iron and steel industry broadly consists of:

- Primary facilities that produce both iron and steel;
- Secondary steelmaking facilities;
- Iron production facilities; and
- Offsite production of metallurgical coke.

Figure 4.1 illustrates the main processes for iron and steel production: metallurgical coke production, sinter production, pellet production, iron ore processing, iron making, steelmaking, steel casting and very often combustion of blast furnace and coke oven gases for other purposes. The main processes may occur under what is referred to as an 'integrated' facility and typically include blast furnaces, and basic oxygen steelmaking furnaces (BOFs), or in some cases open hearth furnaces (OHFs). It is also common for parts of the production to be offsite under the responsibility of another operator such as an offsite coke production facility.

In some countries, there will be coke production facilities that are not integrated with iron and steel production (i.e., 'offsite'). This chapter provides guidance for estimating emissions of CO_2 and CH_4 from all coke production to ensure consistency and completeness. Countries should estimate emissions from onsite and offsite coke production separately under higher tiers as the by-products of onsite coke production (e.g., coke oven gas, coke breeze, etc.) are often used during the production of iron and steel.

Primary and secondary steel-making:

Steel production can occur at integrated facilities from iron ore, or at secondary facilities, which produce steel mainly from recycled steel scrap. Integrated facilities typically include coke production, blast furnaces, and BOFs, or in some cases OHFs. Raw steel is produced using a basic oxygen furnace from pig iron produced by the blast furnace and then processed into finished steel products. Pig iron may also be processed directly into iron products. Secondary steelmaking most often occurs in electric arc furnaces (EAFs). In 2003, BOFs accounted for approximately 63 percent of world steel production and EAFs approximately accounted for 33 percent; OHF production accounted for the remaining 4 percent but is today declining.

Iron production:

Iron production can occur onsite at integrated facilities or at separate offsite facilities containing blast furnaces and BOFs. In addition to iron production via blast furnace, iron can be produced through a direct reduction process. Direct reduction involves the reduction of iron ore to metallic iron in the solid state at process temperatures less than 1000°C.

Metallurgical coke production:

Metallurgical coke production is considered to be an energy transformation of fossil fuel, and as a result the combustion and fugitive emissions from coke production should be reported in the Energy Sector. Methodologies for emissions from the combustion of fuels in coke production are included in the Energy volume, section 2.3, whilst the methodologies for fugitive emissions (including emissions from flaring of Coke Oven Gas(CGO)) are included in the Energy sector, section 4.3. Combustion emissions from coke production are reported in 1A1ci (see Volume 2: Energy, table 2.1), whilst fugitive (including flaring) emissions are reported in 1B1cii (see Volume 2: Energy, table 4.3.4).

Emission estimation methodologies for coke production are presented here in Volume 3, however, because the activity data used to estimate emissions from energy and non-energy in integrated iron and steel production have significant overlap.

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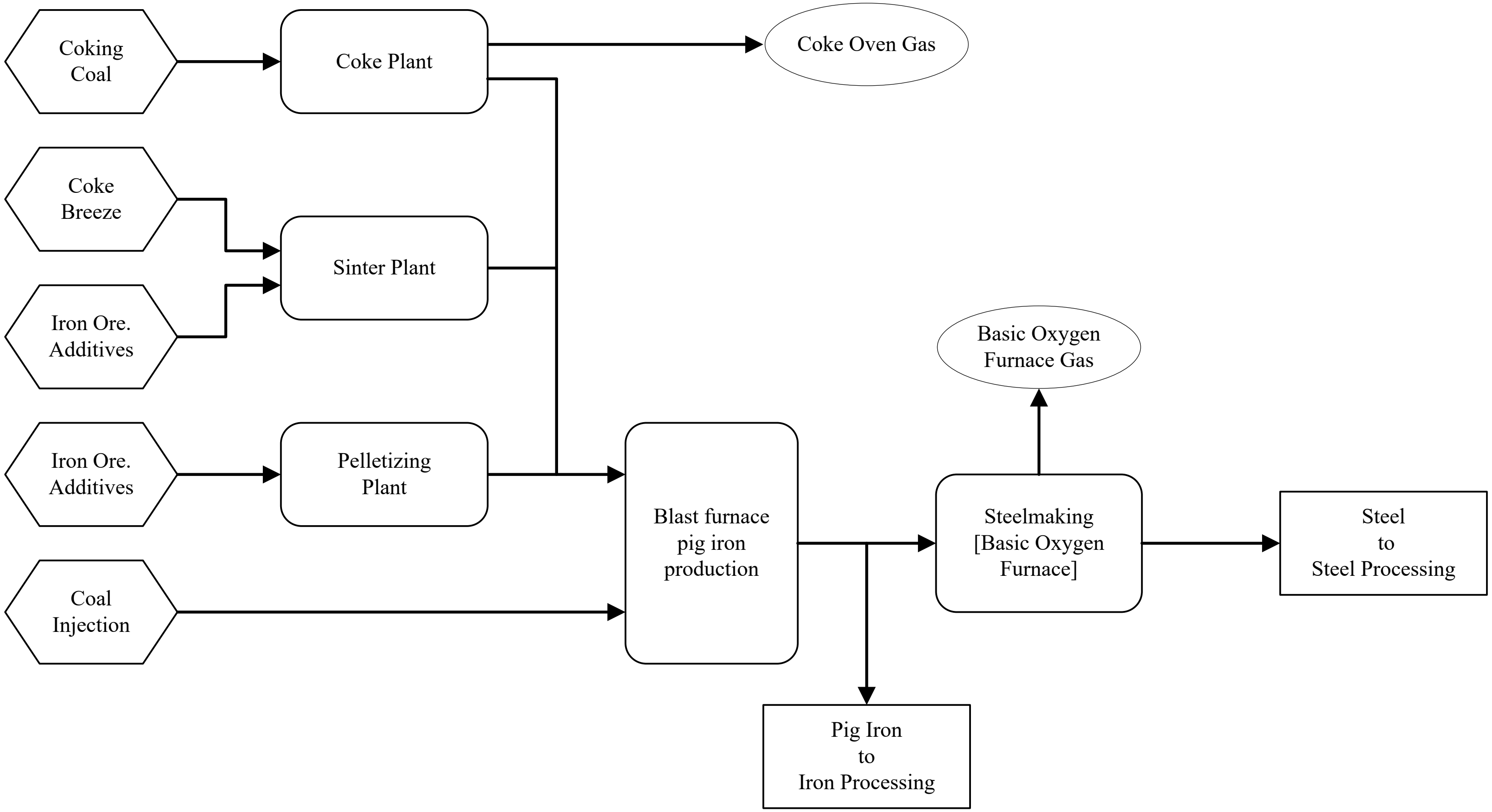
[1] No methodologies are provided for N_2O emissions. These emissions are likely to be small, but countries can calculate estimates provided they develop country-specific methods based on researched data.

Figure 4.1 Illustration of main processes for integrated iron and steel production*



*Modified from: European conference on "The Sevilla Process: A Driver for Environmental Performance in Industry" Stuttgart, 6 and 7 April 2000, BREF on the Production of Iron and Steel – conclusion on BAT, Dr.Harald Schoenberger, Regional State Governmental Office Freiburg, April 2000. (Schoenberger, 2000)

4.2.1 Introduction

No refinement.

4.2.2 Methodological issues

Inventory compilers should ensure that all emissions from coke production are included in their inventories but are not double-counted. The section below highlights methodological options and indicates *good practice* in terms of reporting allocations, noting that methodologies are also presented in the Energy sector for combustion emissions (Volume 2: Energy, section 2.1) and fugitive emissions (Volume 2: Energy, section 4.3) from coke production.

The coke-making process comprises: (1) coal handling and preparation, including transportation, discharge, storage, crushing, bed blending, that in all cases cause dust emissions, but not GHG emissions, and other following stages where GHG emissions do occur, which are (2) coke oven battery operations, including coal charging, chamber heating and firing , coking, coke pushing and quenching and coke handling (i.e. storing, transporting, crushing and screening), and (3) coke oven gas treatment. The term 'coking' refers to the Carbonisation process that takes place in the ovens which is a thermal distillation process that removes volatile matter from the coking coal, in the form of gases or liquids, to produce coke. There are two technological options for coke-making which differ primarily in the treatment of coke-making by-products:

- Coke production *with* by-product recovery where organic liquids, including coal tar and light oil, are recovered;
- Coke production *without* by-product recovery, where all ovens operate under negative pressure and, consequently, there are no leakages under normal operating conditions. All the by-products are retained and burned, instead of recovered. This process is usually accompanied by heat recovery and, in many cases, also the cogeneration of electricity.

GHG emission sources from metallurgical coke production include:

- Stack emissions which comprise GHG emissions from both the carbonisation (fuel transformation) of the coal, and from fuel combustion. These emissions should all be reported in the Energy Sector, in Manufacture of Solid Fuels in IPCC category 1.A.1.c. The emission estimation methodology from the carbonisation of coal, including emissions from fuel combustion to heat the coke ovens, is presented here as there is a significant overlap with the activity data used for iron and steel production. The Energy Volume (Chapter 2 Volume 2 of *2006 IPCC Guidelines)* also presents an estimation methodology for combustion emissions is described in Chapter 2 Volume 2 of *2006 IPCC Guidelines* that may be applied to the activity data of fuel use to heat the coke ovens; therefore, care must be taken not to duplicate the emission estimates from fuel use in coke manufacture, within Energy and Industrial Processes and Product Use (IPPU).
- Fugitive emissions, which comprise:
    - Diffuse emissions (i.e. not emitted via stacks or vents) that occur during regular or irregular operations, originating from the transportation of coke, the use of ascension pipes, coke pushing, quenching and leakages in the battery. These diffuse emission sources are inherently difficult to monitor and therefore to quantify. CH_4 is the only GHG with significant diffuse emissions. These emissions should be reported under the Energy Sector, in the Fugitive emissions subsection (IPCC category 1.B.1c), and the methodology to estimate them is presented in Chapter 4 Volume 2 of the *2019 Refinement*.
    - Flaring emissions of, inter alia, CO_2, CH_4 and N_2O which occur primarily during emergencies and COG consumer maintenance. Where coke production is integrated with iron and steel manufacturing facilities, COG is usually burned as part of a gas mixture that contains blast furnace gas (BFG) and other gases produced, such as converter gas. Where these gases are used for the coke production, these emissions should be reported under the Energy Sector: (1) CH_4 and N_2O in IPCC category 1.B.1c , and the methodology to estimate them is presented Section 4.3.2.2 Chapter 4 Volume 2 of the *2019 Refinement*, and (2) CO_2 should also be reported under IPCC 1.B.1c category, except for when the simplified mass-balance approach is applied (Tier 1.b) and in that instance the CO_2 emissions should be reported together with direct emissions under the category 1.A.1.c. (Refer to Box 4.0) .
    - Venting emissions of un-burned COG rarely occur and are considered negligible.

Table 4.1a presents a summary of the allocation of emissions from metallurgical coke production.

TABLE 4.1A (NEW)
EMISSION ALLOCATION FROM METALLURGICAL COKE PRODUCTION

Processes and gases		**Carbonisation emissions**	**Combustion emissions**	**Fugitive emissions**	
				Diffuse emissions	**Flaring emissions**
Coal charging	CO_2	NO	NO	NO	NO
	CH_4	NO	NO	1.B.1c (3)	NO
	N_2O	NO	NO	NO	NO
Chamber heating and firing	CO_2	NO	1.A.1.c (2)	NS	NO
	CH_4	NO		1.B.1c (3)	NO
	N_2O	NO		NO	NO
Coking	CO_2	1.A.1.c (1)	NO	NS	NO
	CH_4			1.B.1c (3)	NO
	N_2O			NO	NO
Coke pushing	CO_2	NO	NO	NS	NO
	CH_4	NO	NO	1.B.1c (3)	NO
	N_2O	NO	NO	NO	NO
Coke quenching	CO_2	NO	NO	NS	NO
	CH_4	1.A.1.c (1)	NO	1.B.1c (3)	NO
	N_2O	NO	NO	NO	NO
Emergencies and COG consumer maintenance among other reasons	CO_2	NO	NO	NS	1.B.1c (3) and 1.A.1.c (1) (4)
	CH_4	NO	NO	1.B.1c (3)	1.B.1c
	N_2O	NO	NO	NS	

Note:

NS: Not significant, NO: not occurring

(1) Methodology described in this chapter

(2) Methodology described in Chapter 2, Volume 2 of *2006 IPCC Guidelines*

(3) Methodology described in Chapter 4 Volume 2 of the *2019 Refinement*

(4) When simplified carbon balance approach is used (Tier 1.b)

4.2.2.1 CHOICE OF METHOD: METALLURGICAL COKE PRODUCTION – NON FUGITIVE EMISSIONS

This section outlines three Tiers for calculating CO_2 and CH_4 emissions from metallurgical coke production. In all cases, the methods encompass emissions from carbonisation and fuel combustion.

The Tier used to estimate emissions will depend on the quantity and quality of data that is available for national inventory compilers. The decision tree in Figure 4.6 will help select the Tier to be used to estimate CO_2 emissions. For CH_4 emissions, the decision tree is presented in Figure 4.8a.

There are two Tier 1 method options to estimate CO_2 emissions, depending on the activity data that are available:

- Tier 1 a: Where only metallurgical coke production data are available, the methodology applies a default emission factor given in Table 4.1, corresponding to the type of coke production technology. This methodology takes into consideration default emission factors derived from stack measurements, comprising the emissions from carbonisation (fuel transformation) and combustion, reflecting that there is no practical way to measure the two parameters separately. Where this method is applied, the corresponding CO_2 fugitive emissions from flaring should be estimated according to the methodology described in Section 4.3.2.2 Chapter 4 Volume 2 of the *2019 Refinement* (category 1.B.1c).

- Tier 1 b: Where, in addition to data on metallurgical coke production, the country also has data on the consumption of metallurgical coal, then it is *good practice* to use the simplified carbon mass balance approach, assuming that all coke oven gas is combusted for coke production. This simple carbon balance method encompasses all carbon that may be released via fugitive emissions (including unintended releases, flaring) and from the consumption of coke oven by-products. In most countries with coke production, the required activity data for this method are readily available from national statistics and/or operators, and as this method is associated with lower uncertainty than the Tier 1a approach, it is the preferred Tier 1 method where the activity data are available.

The Tier 2 method to estimate CO_2 emissions is based on the carbon mass balance approach, using national statistical data on the inputs and outputs of carbonaceous materials to coke production. Where country-specific carbon content data derived from national fuel characteristics are available, it is *good practice* to use them. Otherwise, a hybrid methodology[2] can be used, selecting the default carbon content data provided in Table 4.3, provided that coke production is not a *key category*, in which case country-specific data are required.

The Tier 3 method to estimate CO_2 emissions requires plant-specific emissions measurement data or modelling results, combined with plant-specific activity data and plant-specific carbon content data for the carbon mass balance approach, for those sources where measurement data are not available. Where models are used to estimate emissions (for example, a model that combines a carbon mass balance with measurements), it is *good practice* to conduct model verification to present evidence to justify that the model outputs reflect the facility performance. Further, it is *good practice* to fully document the data and assumptions applied within the model, the sensitivity of the model to key data and assumptions, and the associated uncertainty with modelling results.

Where stack emission measurements are used, it is *good practice* for inventory compilers to document the sampling protocols and analytical methods applied, and to present supporting information to justify that the measurement results reflect plant performance, such as information on the frequency and duration of the measurements, the variability of the process and its GHG emissions and whether the plant was operating under normal conditions.

BOX 4.0 (NEW)
FLARING ACTIVITIES IN METALLURGICAL COKE AND IRON AND STEEL PRODUCTIONS

Gaseous products from metallurgical coke and iron and steel production are mainly used for the generation of heat and electricity, and in some cases as reducing agents. There is a minor proportion of the total gas produced, usually less than 5 percent, which is lost from the production stream and flared, mainly during emergencies or consumer maintenance.

Integrated facilities usually flare a mix of the gases produced, including coke oven gas (COG), blast furnace gas (BFG) and Linz-Donawitz (converter) Gas (LDG) [*also known as basic oxygen furnace gas (BOFG)*], at the same stacks. This situation represents a challenge for the GHG emissions reporting, because:

- GHG emissions from COG flaring should be reported under the Energy Sector;
- GHG emissions from BFG and LDG flaring should be reported under IPPU.

Therefore, in an integrated steelworks, where flares of combined gases are occurred and therefore the individual estimates for flaring of COG, BFG and LDG cannot be determined, then it is *good practice* to report all flaring emissions in IPPU to minimise the risk of double-counting, and to apply methodologies that minimise the overall uncertainty in the inventory.

COG has a high energy content and losses to flaring are minimised as a result, to typically less than 2 percent of COG production.

BFG is also used widely for heat and power-raising, with flaring activity often determined by gas demand on plant, and typically up to 20 percent flared. LDG may be captured and used around the facility to meet fuel combustion demand, but is often completely flared and in some cases may be directly vented to atmosphere.

The typical industry flaring rates are: COG 0.3-2 percent; BFG 0.5-20 percent; LDG 5-100 percent.

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[2] 'Hybrid' refers to a methodology based on the complete carbon balance approach, with the use of default carbon content data.

Table 4.1b summarizes the activity data and the emission factors to be used to estimate CO_2 emissions for the different Tiers.

TABLE 4.1B (NEW)
TIERS TO ESTIMATE CO_2 EMISSIONS FROM METALLURGICAL COKE PRODUCTION – NON FUGITIVE EMISSIONS

Method	AD	EF	Technology	Limitations/Comments	Tier
Production-based	Metallurgical coke produced in the country	Default EF (Table 4.1)	This method can be applied to technologies with and without by-product recovery.	The production-based method should not be used to estimate emissions in conjunction with the carbon balance approach for iron and steel production, where the coke ovens operate within an integrated steelworks, to avoid double-counting.	Tier 1a
Simplified carbon balance (where only limited AD are available)	Coking coal consumed and metallurgical coke produced in the country	Carbon content of coking coal and coke (Defaults are presented in Table 4.3)	This method assumes 100% consumption of COG within the coke making process, thus it is more applicable to cases where by-products are not recovered.	If this method is applied, do not also calculate CO_2 emissions from fugitives and flaring using the methods described in the Energy volume, to avoid double-counting.	Tier 1b
National Carbon Balance method (country-specific EFs)	National data on all inputs (raw materials and fuels, i.e. coking coal) and on all outputs (products and by-products: coke, COG, tars and benzenes, flaring)	Country-specific carbon contents of inputs and outputs	All technologies	If country-specific carbon contents are not available for all inputs and outputs, the default carbon contents from Table 4.3 may be applied with the hybrid method, but this will be considered a Tier 1 / Tier 2 approach which is not appropriate for a *key category*.	Tier 2
Aggregated plant-specific carbon balance method (country-specific EFs)	Installation-level data on all inputs (*as described above*) and outputs (*as described above*)	Plant-specific carbon contents of inputs and outputs	All technologies	n/a	Tier 3a
Installation-level measurement data or plant specific modelling data	n/a	n/a	All technologies	Emissions measurement data and/or modelling results must be complete for all emission sources at the coke plant and must comply with measurement protocols and/or verification processes for modelling.	Tier 3b

The methodologies to estimate CH_4 emissions relate to emissions from stacks, using default emission factors (Tier 1a), country specific emission factors (Tier 2) or measurements/models (Tier 3). The methodology to estimate CH_4 fugitive emissions is described in Section 4.3.2.2 Chapter 4 Volume 2 of the *2019 Refinement* (IPCC category 1.B.1c).

TIER 1 METHOD

Tier 1 a: Production based method

Applying this method requires the amount of coke produced (tonnes) in the country and a default emission factor, given in Table 4.1. The following equations are used:

EQUATION 4.1 (UPDATED)
CO_2 EMISSIONS FROM COKE PRODUCTION (TIER 1A)

$$E_{CO_2,energy} = CK \bullet EF_{CO_2}$$

EQUATION 4.1A (NEW)
CH_4 EMISSIONS FROM COKE PRODUCTION (TIER 1A)

$$E_{CH_4,\,energy} = CK \bullet EF_{CH_4}$$

Where:

$E_{CO_2,energy}$ or $E_{CH_4,energy}$ = emissions of CO_2 or CH_4 from coke production, in tonnes of CO_2 or tonnes CH_4, to be reported under the Energy Sector, category 1.A.1c.

CK = quantity of coke produced nationally, tonnes

EF = emission factor, tonnes CO_2/tonnes coke produced or tonnes CH_4/tonnes coke produced (Table 4.1)

Tier 1 b: Simplified carbon balance method

The Tier 1 b method assumes that all of the coke oven by-products are transferred off site and that all of the coke oven gas produced is burned on-site for energy recovery. Applying this method requires data on the amount of coking coal used as raw material and the amount of metallurgical coke produced. The following equation, with a default carbon content given in Table 4.3, is used:

EQUATION 4.1B (NEW)
CO_2 EMISSIONS FROM METALLURGICAL COKE PRODUCTION (TIER 1B)

$$E_{CO_2,energy} = (CC \bullet C_{cc} - CK \bullet C_{CK}) \bullet \frac{44}{12}$$

Where:

$E_{CO_2,energy}$ = CO_2 emissions to be reported in the Energy Sector category 1.A.1c, tonnes

CC = quantity of coking coal consumed for coke production in the country, tonnes

CK = quantity of coke produced in the country, tonnes

C_{CC} = default carbon content of coking coal, tonnes C/tonne coal

C_{CK} = default carbon content of metallurgical coke, tonnes C/tonne coke

TIER 2 METHOD

The Tier 2 method to estimate CO_2 emissions is appropriate where national statistics on process inputs and outputs from integrated and non-integrated coke production processes are available, and where country-specific carbon contents for process inputs and outputs are available

EQUATION 4.2 (UPDATED)

CO_2 EMISSIONS FROM METALLURGICAL COKE PRODUCTION

$$E_{CO_2,\,energy} = [CC \bullet C_{CC} + \sum_a (PM_a \bullet C_a) + BG \bullet C_{BG} - CO \bullet C_{CO} - COG \bullet C_{COG} - \sum_b (COB_b \bullet C_b) - E_{flaring}] * 44/12$$

Where:

$E_{CO_2,energy}$ = CO_2 emissions to be reported in the Energy Sector category 1.A.1c, tonnes

CC = quantity of coking coal consumed in the country, tonnes

PM_a = quantity of process materials *a*, other than those listed as separate terms, i.e. natural gas, fuel oil or converter gas, consumed in the country for metallurgical coke production, tonnes

BG = quantity of blast furnace gas consumed in coke ovens in the country, tonnes

CO = quantity of metallurgical coke produced in the country, tonnes

COG = quantity of coke oven gas produced but not recirculated and therefore not consumed for metallurgical coke production, tonnes

COB_b = quantity of coke oven by-product *b* (e.g. COG, coal tar, light oil) produced, and either transferred offsite or to other facilities or flared, tonnes

$E_{flaring}$ = CO_2 emissions from flaring, tonnes, deducted from the carbon mass balance, as the corresponding emissions are estimated as fugitive emissions using the methodology described in Section 4.3.2.2 Chapter 4 Volume 2 of the *2019 Refinement*

C_x = country specific carbon content of material input or output *x*, tonnes C/tonne material

[“C_X” is a generic term intended to cover parameters above such as “C_{CC}” – coking coal; “C_{CO}” – metallurgical coke; etc.]

If country specific carbon contents for all the input and output materials included in Equation 4.2 are not available, default carbon content from Table 4.3 could be used. In this case the methodology is a hybrid between Tier 1 and Tier 2, and is not appropriate if the metallurgical coke production is a *key category*.

For CH_4, in Tier 2 methodology inventory compilers can use the amount of coke produced, in combination with country specific emission factor.

TIER 3 METHOD

Unlike the Tier 2 method, Tier 3 uses plant specific data, considering that plants can differ substantially in their technology and process conditions.

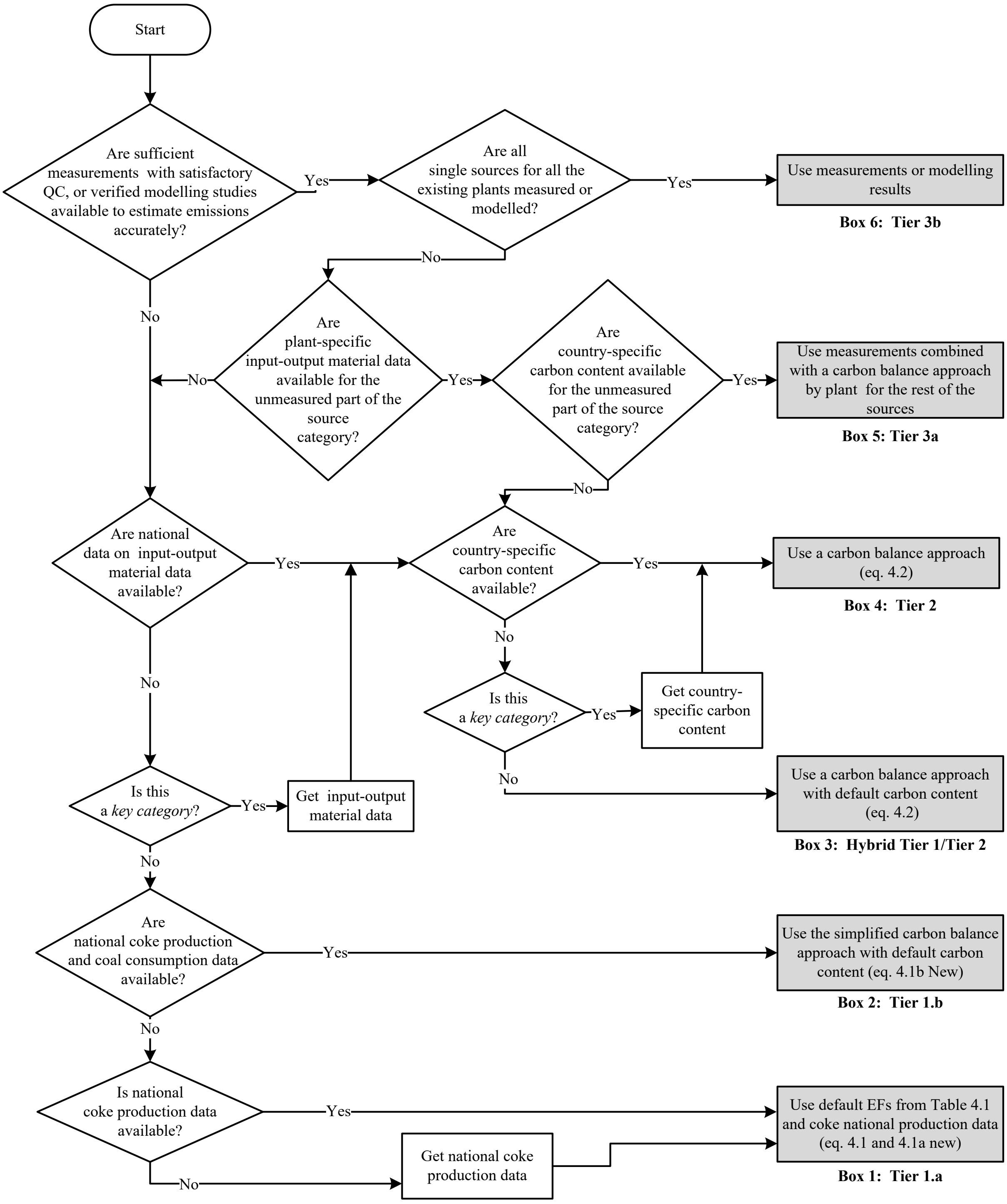
Tier 3 comprises two approaches for CO_2 and only one for CH_4:

- For CO_2 and CH_4:
    - monitoring data or modelling of stack emissions, from both carbonisation and from fuel combustion; flaring of COG is excluded, as it is included in Section 4.3. Chapter 4 Volume 2 of the *2019 Refinement* (category 1.B.1c).
- For CO_2:
    - the carbon mass balance approach, with plant-specific carbon contents of all the materials used and produced.

If actual measured CO_2/CH_4 emissions data are available from all the stacks present in all the coke production plants in the country, these data could be aggregated and used directly to account for the national emissions from metallurgical coke production. The total national emissions will be equal to the sum of emissions reported from each facility. It is a *good practice* to apply QA/QC to the monitoring data, following the recommendations included in Volume 1 Chapter 6 of the *2019 Refinement.*

A Tier 3 approach for one or more plants could be combined with lower Tiers approaches for other plants to derive a national estimate. In case the plant-specific CO_2 emissions data are not available for part or for all sources in the country, the CO_2 emissions for the unmeasured sources could be estimated using plant specific activity data applying a carbon mass balance with country specific carbon contents, using Equation 4.2.

Figure 4.6 (Updated) Estimation of CO_2 emissions from metallurgical coke production



Notes:

[1] Measurements corresponding to fugitive emissions should be estimated and reported with the methodology described in Chapter 4 Volume 2 of the *2019 Refinement*.

4.2.2.2 CHOICE OF METHOD: IRON AND STEEL PRODUCTION

This section outlines three Tiers for calculating CO_2 and CH_4 emissions and two Tiers N_2O emissions from iron and steel production. Decision trees are presented in Figures 4.7, 4.8a, 4.8b and 4.8c.

The Tier 1 method is based on national production data and default emission factors. The method derives estimates of CO_2 emissions based on assumptions regarding the quantity of material inputs to sinter production and to iron and steel production, rather than through use of more detailed activity data on process inputs. Therefore, the method is associated with higher uncertainties, due to the reliance on these assumptions. Consequently, the Tier 1 method is only appropriate where sinter production and iron and steel production are not a *key category(ies)*.

The Tier 2 method to estimate CO_2 emissions is based on the carbon mass balance approach, using national statistical data on the inputs and outputs of carbonaceous materials. Where country-specific carbon content data derived from national fuel characteristics are available, it is *good practice* to use them. Otherwise, a hybrid methodology[3] can be used, selecting the default carbon content data provided in Table 4.3, provided that iron and steel production is not a *key category*, in which case country-specific data are required.

The Tier 3 method is based on the use of stack measurements and/or modelling results:

Where stack emission measurements are used, it is *good practice* for inventory compilers to document the sampling protocols and analytical methods applied, and to present supporting information to justify that the measurement results reflect plant performance, such as information on the frequency and duration of the measurements, the variability of the process and its GHG emissions and whether the plant was operating under normal conditions.

Where models are used to estimate emissions, it is *good practice* to conduct model verification to present evidence to justify that the model outputs reflect the facility performance. Further, it is *good practice* to fully document the data and assumptions applied within the model, the sensitivity of the model to key data and assumptions, and the associated uncertainty with modelling results.

METHODOLOGY FOR ESTIMATING CO_2 EMISSIONS

Tier 1 method – production-based emission factors

The Tier 1 approach for emissions from iron and steel production is to multiply default emission factors by national production data, as shown in Equation 4.4. Because emissions per unit of steel production vary widely depending on the method of steel production, it is *good practice* to determine the share of steel produced in different types of steelmaking processes, calculate emissions for each process, and then sum the estimates. Equation 4.4 considers steel production from BOF, EAF, and Open Hearth Furnaces (OHF). In the event that activity data for steel production for each process is not available, default allocation of total national steel production among these three steelmaking processes is provided in Table 4.1 in Section 4.2.2.3.

Equation 4.5 calculates emissions from the blast furnace production of pig iron that is not converted into steel. It is preferable to estimate emissions from this production separately because the emission factors for integrated iron and steel production (BOF and OHF processes) take into account emissions from both iron production and steel production.

A blast furnace is a closed system into which iron-bearing materials (iron ore lump, sinter and/or pellets), additives (slag formers such as limestone) and reducing agents (i.e. coke) are continuously fed from the top of the furnace shaft through a charging system that prevents the escape of BFG. A hot air blast, enriched with oxygen and auxiliary reducing agents is injected on the tuyere level providing a counter current of reducing gases. The air blast reacts with the reducing agents to produce mainly carbon monoxide (CO), which in turn reduces iron oxides to metal iron. The liquid iron is collected in the hearth along with the slag and both are cast on a regular basis. The liquid iron is transported in torpedo vessels to the steel plant, and the slag is processed to produce aggregate, granulate or pellets. The blast furnace gas is collected at the top of the furnace. It is treated and distributed around the works to be used as a fuel for heating or for electricity production. The vast majority of GHGs are emitted from the blast furnaces' stove stacks where the combustion gases from the stoves are discharged.

The objective in oxygen steelmaking is to burn (i.e. oxidise) the undesirable impurities contained in the hot metal feedstock. The main elements thus converted into oxides are carbon, silicon, manganese and phosphorus. The purpose of this oxidation process is to reduce the carbon content to a specified level (from approximately 4 – 5 percent to typically 0.01 – 0.4 percent), adjust the contents of desirable foreign elements and to remove undesirable impurities to the greatest possible extent, which are oxidised with the subsequent removal of the off-gas or slag. During the process, a number of additives are used to adjust steel quality and to form slag. The major emission point for GHGs from the BOF is the furnace exhaust gas that is discharged through a stack after gas cleaning. The gases produced during oxygen blowing (converter gas) contain large amounts of carbon monoxide. In most steelmaking plants, measures have been taken to recover the converter gas and use it as an energy source. The CO-rich flue-gas can be collected, cleaned and buffered for subsequent use as fuel. The carbon is removed as CO and

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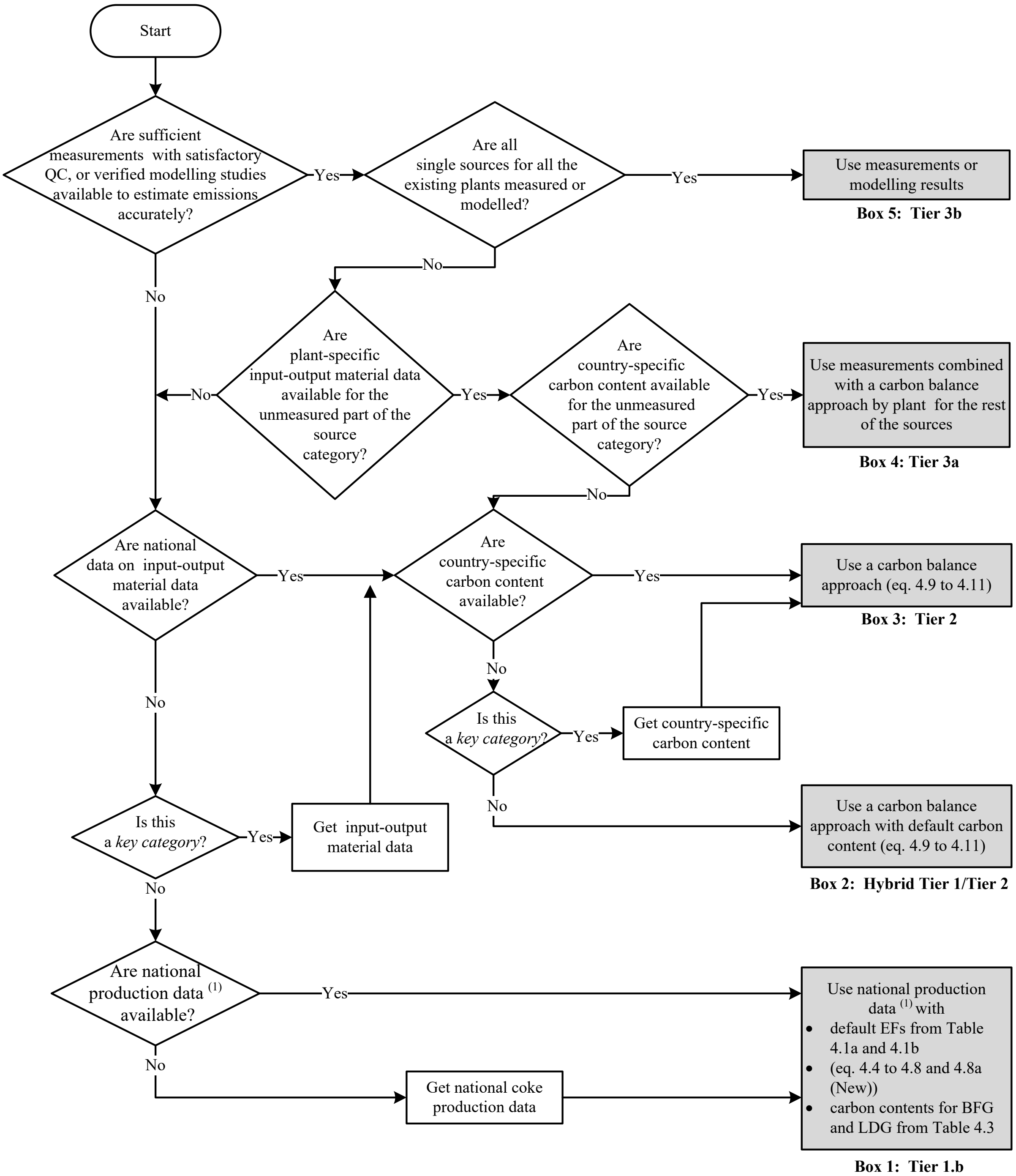
[3] 'Hybrid' refers to a methodology based on the complete carbon balance approach, with the use of default carbon content data.

CO_2 during the oxygen blow. Carbon may also be introduced to a much smaller extent from fluxing materials and other process additives that are charged to the furnace.

Figure 4.7 (Updated) Decision tree for estimation of CO_2 emissions from iron and steel production



Note:
(1) National production data refers to the productions of (1) steel; (2) pig iron not processed into steel; (3) direct reduced iron; (4) sinter; (5) pellet; (6) blast furnace gas and (7) converter gas.

Figure 4.8a (New) Decision tree for estimation of CH_4 emissions from coke production

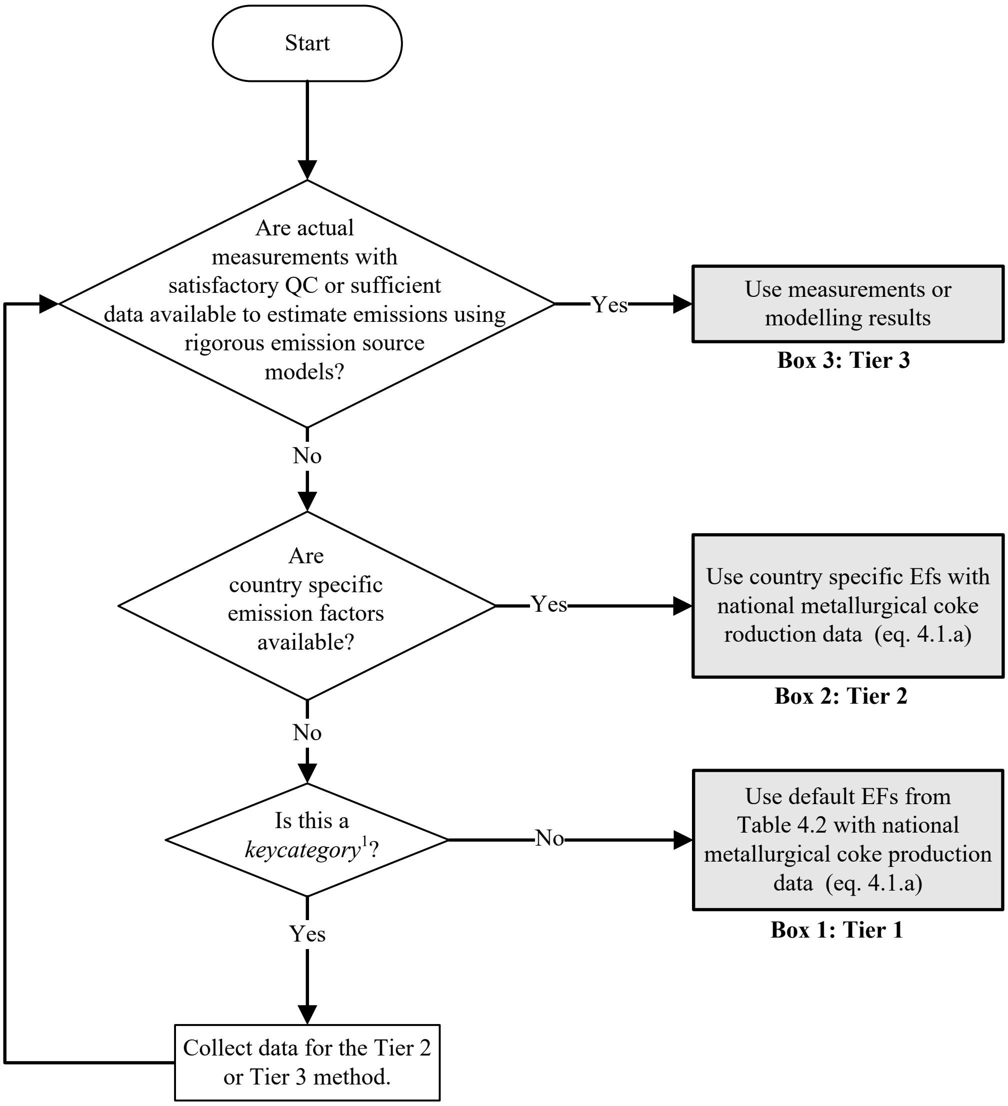
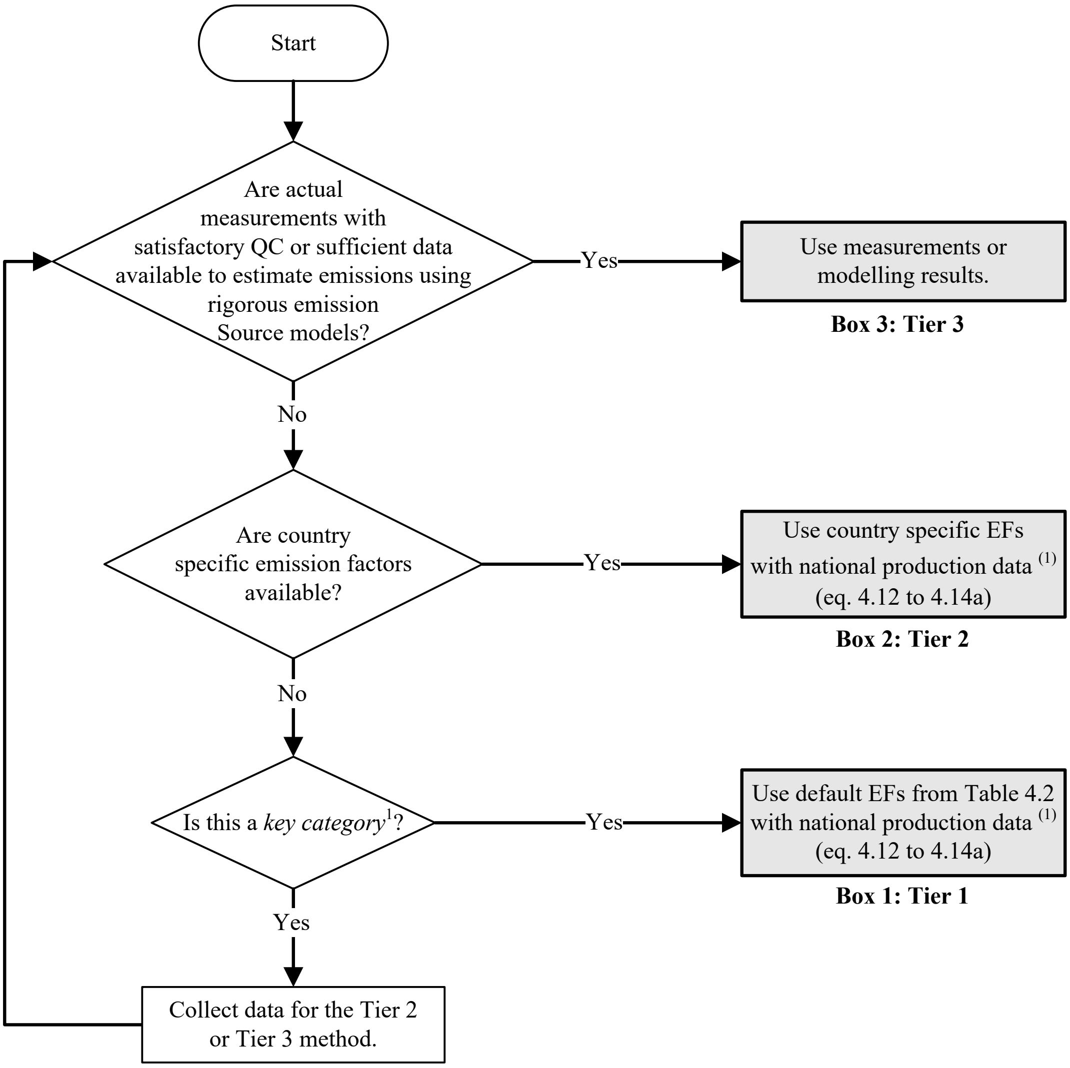
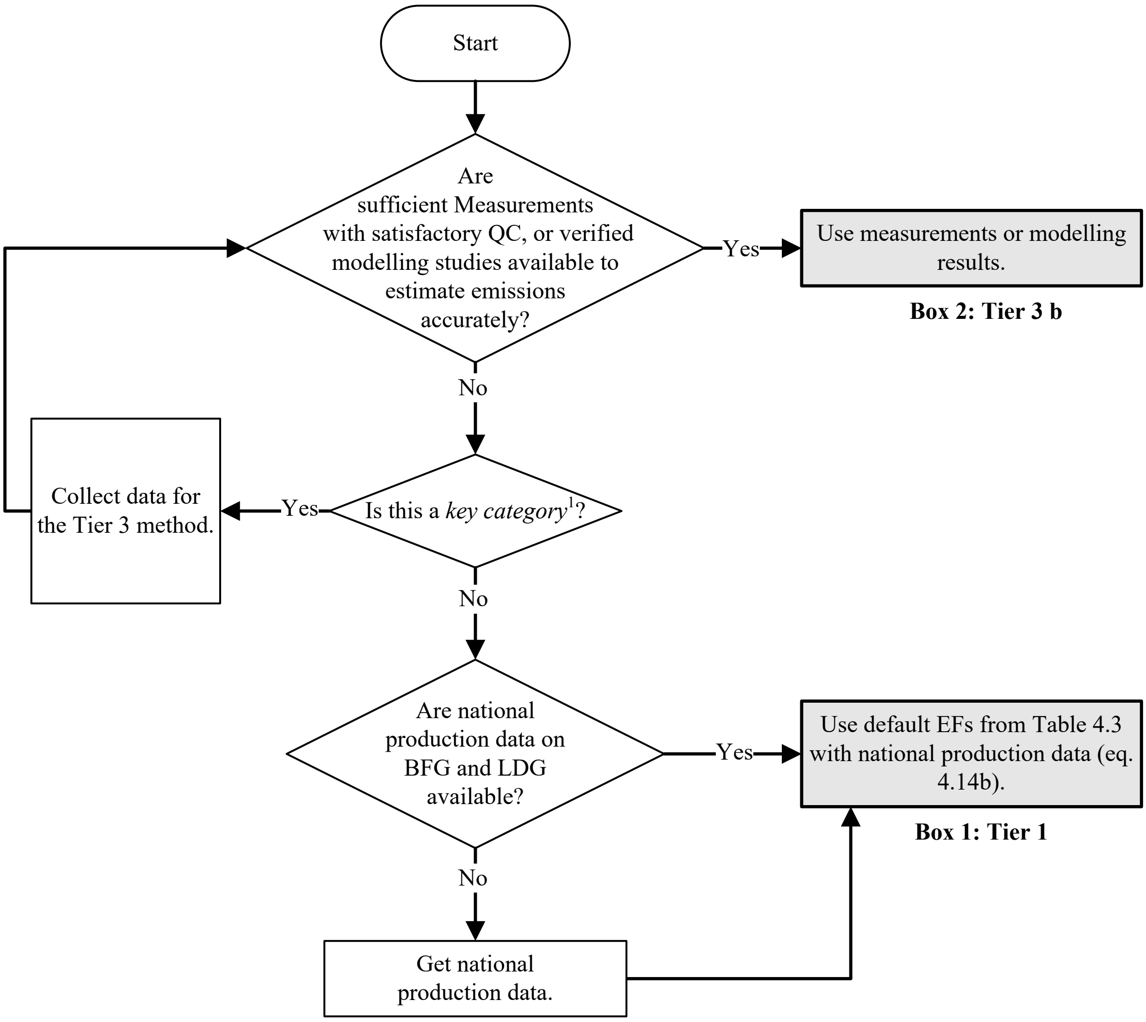


Figure 4.8b (Updated) Decision tree for estimation of CH_4 emissions from iron and steel production



Note: (1) National production data refers to the productions of (1) sinter; (2) pig iron; (3) direct reduced iron; (4) blast furnace gas and (5) converter gas.

Figure 4.8c (New) Decision tree for estimation of N_2O emissions from iron and steel production



Equation 4.6 calculates CO_2 emissions from production of Direct Reduced Iron (DRI) for the Tier 1 method using a CO_2 emission factor.

In sinter plants CO_2 emissions occur during fuel combustion in burners and as a result of leakages from the feed materials, including coke fines and other carbonaceous materials. It is *good practice* to estimate separately the emissions from national sinter production and national pellet production, using Equations 4.7 and 4.8. which should be used if the inventory compiler does not have detailed information about the process materials used. If the process materials are known, emissions should be calculated using the Tier 2 method.

Equation 4.8a calculates CO_2 emissions from blast furnace gas (BFG) and converter gas (LDG) flaring, considering that 20 percent (vol) of the BFG is removed from the production stream and then flared, and that all (100 percent) of the LDG is also flared. (see Box 4.0)

Total emissions are the sum of Equations 4.4 to 4.8 (including the Equation 4.8a).

EQUATION 4.4
CO_2 EMISSIONS FROM IRON AND STEEL PRODUCTION (TIER 1)

$$\text{Iron \& Steel: } E_{CO_2,\, non-energy} = BOF \bullet EF_{BOF} + EAF \bullet EF_{EAF} + OHF \bullet EF_{OHF}$$

EQUATION 4.5
CO_2 EMISSIONS FROM PRODUCTION OF PIG IRON NOT PROCESSED INTO STEEL (TIER 1)

$$\text{Pig Iron Production: } E_{CO_2,\, non-energy} = IP \bullet EF_{IP}$$

EQUATION 4.6
CO_2 EMISSIONS FROM PRODUCTION OF DIRECT REDUCED IRON (TIER 1)

$$\text{Direct Reduced Iron: } E_{CO_2,\, non-energy} = DRI \bullet EF_{DRI}$$

EQUATION 4.7
CO_2 EMISSIONS FROM SINTER PRODUCTION (TIER 1)

$$\text{Sinter Production: } E_{CO_2,\, non-energy} = SI \bullet EF_{SI}$$

EQUATION 4.8
CO_2 EMISSIONS FROM PELLET PRODUCTION (TIER 1)

$$\text{Pellet Production: } E_{CO_2,\, non-energy} = P \bullet EF_{P}$$

EQUATION 4.8A (NEW)
CO_2 EMISSIONS FROM BFG AND LDG FLARING (TIER 1)

$$E_{CO_2,\, non-energy} = BFG \bullet (EF_{CO_2})_{BFG\ flaring} + LDG \bullet (EF_{CO_2})_{LDG\ flaring}$$
$$= BFG \bullet (R_{BFG\ flared} \bullet CC_{BFG} \bullet \frac{44}{12}) + LDG \bullet (R_{LDG\ flared} \bullet CC_{LDG} \bullet \frac{44}{12})$$

Where:

$E_{CO_2,\, non-energy}$ = emissions of CO_2 to be reported in IPPU Sector, tonnes

BOF = quantity of BOF crude steel produced, tonnes

EAF = quantity of EAF crude steel produced, tonnes

OHF = quantity of OHF crude steel produced, tonnes

IP = quantity of pig iron production not converted to steel, tonnes

DRI = quantity of Direct Reduced Iron produced nationally, tonnes

SI = quantity of sinter produced nationally, tonnes

P = quantity of pellet produced nationally, tonnes

EF_x = emission factor, tonnes CO_2/tonne *x* produced

$\left(EF_{CO_2}\right)_{BFG\ flaring}$ = emission factor, tonnes CO_2/tonnes of BFG produced

$\left(EF_{CO_2}\right)_{LDG\ flaring}$ = emission factor, tonnes CO_2/tonnes of LDG produced

BFG = blast furnace gas produced nationally, tonnes

LDG = converter gas produced nationally, tonnes

$R_{BFG\ flared}$ = rate of BFG removed from the production steam and then flared. If this data is not available, a default value of 0.2 can be assumed (see Box 4.0)

$R_{BFG\ flared}$ = rate LDG removed from the production steam and then flared. If this data is not available, a default value of 1.0 can be assumed (see Box 4.0)

CC_{BFG} = carbon content of blast furnace gas, tonnes C/tonne

CC_{LDG} = carbon content of converter gas, tonnes C/tonne

In an integrated plant, the emissions from the combustion of blast furnace gas, coke oven gas and converter gas to produce heat for different needs within the steelworks (rolling mills, hot rolling mill, plate mill, bar mill, cold rolling mill, coating, pipe) and to produce electricity at the internal power plant to cover the internal needs should be reported under IPPU (see Section 4.2.2.5). The methodology for these estimations is described in Chapter 2 Volume 2 of the *2006 IPCC Guidelines.*

Tier 2 method

The Tier 2 method is appropriate where the inventory compiler has access to national data on the use of process materials for iron and steel production, sinter production, pellet production and direct reduced iron production. In addition, as discussed in Section 4.2.2.5, there are several other process inputs and outputs that could be considered under Tier 2. This data may be available from governmental agencies responsible for manufacturing or energy statistics, business or industry trade associations or individual iron and steel companies. The Tier 2 method will produce a more accurate estimation compared to the Tier 1 method, as it considers the actual quantity of inputs that contribute to CO_2 emissions.

Total emissions are the sum of Equations 4.9, 4.10 and 4.11. for those processes that occur in the country.

EQUATION 4.9 (UPDATED)
CO_2 EMISSIONS FROM IRON AND STEEL PRODUCTION (TIER 2)

$$E_{CO_2,non-energy} = [PC \bullet C_{PC} + \sum_a (COB_a \bullet C_a) + CI \bullet C_{CI} + L \bullet C_L + D \bullet C_D + CE \bullet C_{CE} + \sum_b (O_b C_b) + COG \bullet C_{COG} - S \bullet C_S - IP \bullet C_{IP} - BFG \bullet C_{BFG}] \bullet \frac{44}{12}$$

EQUATION 4.10 (UPDATED)
CO_2 EMISSIONS FROM SINTER PRODUCTION (TIER 2)

$$E_{CO2,non-energy} = \begin{bmatrix} CBR \bullet {}_{CBR} + COG \bullet C_{COG} + BFG \bullet C_{BFG} + \\ + \sum_a \left(PM_a \bullet C_a\right) \end{bmatrix} \bullet \frac{44}{12}$$

Where, for iron and steel production:

$E_{CO_2,\ non\text{-}energy}$ = emissions of CO_2 to be reported in IPPU Sector, tonnes

PC = quantity of coke consumed in iron and steel production (not including sinter production), tonnes

COB_a = quantity of onsite coke oven by-product *a*, consumed in blast furnace, tonnes

CI = quantity of coal directly injected into blast furnace, tonnes

L = quantity of limestone consumed in iron and steel production, tonnes

D = quantity of dolomite consumed in iron and steel production, tonnes

CE = quantity of carbon electrodes consumed in EAFs, tonnes

O_b = quantity of other carbonaceous and process material *b*, consumed in iron and steel production, such as sinter, steel and pig iron scrap or waste plastic, tonnes

COG = quantity of coke oven gas consumed in stationary combustion equipment in iron and steel production (such as cowpers, pre-heating ladles etc.), tonnes (or other unit such as GJ. Conversion of the unit should be consistent with Volume 2 Energy)

S = quantity of steel produced, tonnes

IP = quantity of iron produced not converted to steel, tonnes

BFG = quantity of blast furnace gas transferred off site or to other facilities in an integrated plant, tonnes (or other unit such as GJ. Conversion of the unit should be consistent with Volume 2 Energy)

C_x = carbon content of material input or output *x*, tonnes C/(unit for material *x*) [e.g., tonnes C/tonne]

Where, for sinter production:

$E_{CO_2,\ non\text{-}energy}$ = emissions of CO_2 to be reported in IPPU Sector, tonnes

CBR = quantity of purchased and on-site produced coke breeze used for sinter production, tonnes

COG = quantity of coke oven gas consumed in sinter production, tonnes (or other unit such as GJ. Conversion of the unit should be consistent with Volume 2 Energy)

BFG = quantity of blast furnace gas consumed in sinter production, tonnes (or other unit such as GJ. Conversion of the unit should be consistent with Volume 2 Energy)

PM_a = quantity of process material *a*, other than those listed as separate terms, such as anthracite, consumed for sinter production in integrated iron and steel production facilities, tonnes

C_x = carbon content of material input or output *x*, tonnes C/(unit for material *x*) [e.g., tonnes C/tonne]

Equation 4.11 calculates CO_2 emissions from the production of direct reduced iron for the Tier 2 method based on reducing agents consumption and its carbon contents. Emissions from DRI production are derived from combusting fuel, coke breeze, metallurgical coke or other carbonaceous materials.

EQUATION 4.11
CO_2 EMISSIONS FROM DIRECT REDUCED IRON PRODUCTION (TIER 2)

$$E_{CO_2,\, non-energy} = (DRI_{NG} \bullet C_{NG} + DRI_{BZ} \bullet C_{BZ} + DRI_{CK} \bullet C_{CK}) \bullet \frac{44}{12}$$

Where:

$E_{CO_2,\ non\text{-}energy}$ = emissions of CO_2 to be reported in IPPU Sector, tonnes

DRI_{NG} = amount of natural gas used in direct reduced iron production, GJ

DRI_{BZ} = amount of coke breeze used in direct reduced iron production, GJ

DRI_{CK} = amount of metallurgical coke used in direct reduced iron production, GJ

C_{NG} = carbon content of natural gas, tonne C/GJ

C_{BZ} = carbon content of coke breeze, tonne C/GJ

C_{CK} = carbon content of metallurgical coke, tonne C/GJ

Note: Natural Gas has a double role, to provide heat and act as a reducing agent in DRI furnaces.

If country specific carbon contents for all the input and output materials included in Equations 4.9, 4.10 and 4.11 are not available, default carbon contents from Table 4.3 could be used. In this case, the methodology is a hybrid between Tier 1 and Tier 2 and is not appropriate if the iron and steel production is a *key category*.

Tier 3 method

Unlike the Tier 2 method, the Tier 3 method uses plant specific data. The Tier 3 method provides an even more accurate estimate of emission than the Tier 2 method because plants can differ substantially in their technology and process conditions. If actual measured CO_2 emissions data are available from iron and steelmaking facilities, these data can be aggregated to account for national CO_2 emissions. If facility-specific CO_2 emissions data are not available, CO_2 emissions can be calculated from plant-specific activity data for individual reducing agents, exhaust gases, and other process materials and products. The total national emissions will equal the sum of emissions reported from each facility. Equations 4.9 through 4.11 describe the parameters that are necessary for an accounting of plant-specific emissions using the Tier 3 method and plant-specific activity data at a facility level. Plant-specific carbon contents for each material are required for the Tier 3 method.

METHODOLOGY FOR CH_4

When carbon-containing materials are heated in the furnace for sinter production or iron production, the volatiles, including methane, are released. With open or semi-covered furnaces, most of the volatiles will burn to CO_2 above the charge, in the hood and off-gas channels, but some will remain un-reacted as CH_4 and non-methane volatile organic compounds (NMVOC). The amounts depend on the operation of the furnace. Sprinkle-charging will reduce the amounts of CH_4 compared to batch-wise charging. Increased temperature in the hood (less false air) will reduce the content of CH_4 further.

This section describes a Tier 1 default method and a more advanced Tier 2 and Tier 3 methods for CH_4 emissions from iron and steel production.

The Tier 1 method covers CH_4 emissions from sinter production and from iron production, multiplying default emission factors by national production data. Emissions from flaring are consider negligible, as CH_4 in blast furnace gas and in converter gas not significant. The guidance in this section does not cover the release of CH_4 from pelletisation, although the associated emissions may be relevant when anthracite is used. CH_4 may be emitted from steel making processes as well, however those emissions are assumed to be negligible.

Equation 4.12 calculates CH_4 emissions from sinter production, Equation 4.13 from pig iron production and Equation 4.14 from direct reduced iron production.

The total CH_4 emissions are the sum of Equations 4.12, 4.13, 4.14 and 4.14a, for the processes that occur in the country.

EQUATION 4.12
CH_4 EMISSIONS FROM SINTER PRODUCTION (TIER 1)

$$\text{Sinter Production: } E_{CH_4,\, non-energy} = SI \bullet EF_{SI}$$

EQUATION 4.13
CH_4 EMISSIONS FROM BLAST FURNACE PRODUCTION OF PIG IRON (TIER 1)

$$\text{Pig Iron Production: } E_{CH_4,\, non-energy} = PI \bullet EF_{PI}$$

EQUATION 4.14
CH_4 EMISSIONS FROM DIRECT REDUCED IRON PRODUCTION (TIER 1)

Direct Reduced Iron Production: $E_{CH_4,\, non-energy} = DRI \bullet EF_{DRI}$

Where:

$E_{CH_4,\text{ non-energy}}$ = emissions of CH_4 to be reported in IPPU Sector, kg

SI = quantity of sinter produced nationally, tonnes

PI = quantity of iron produced nationally including iron converted to steel and not converted to steel, tonnes

EF_{SI} = emission factor for sinter production, kg CH_4/tonne sinter produced

EF_{PI} = emission factor for pig iron production, kg CH_4/tonne pig iron produced

EF_{DRI} = emission factor for steel by direct reduced iron production, kg CH_4/tonne DRI steel produced

In Tier 2 methodology inventory compilers can use the amount of sinter, pig iron from blast furnace and iron from direct reduction produced nationally, in combination with the corresponding country specific emission factors.

The Tier 3 method uses plant specific emissions data from stack emissions monitoring, or modelling results. The total national emissions will equal the sum of emissions reported from each facility.

METHODOLOGY FOR N_2O

This section describes a Tier 1 default method and a more advanced Tier 3 plant level method for N_2O emissions from iron and steel production. There is no Tier 2 method.

The Tier 1 method covers only N_2O emissions from flaring, multiplying default emission factors by national production data. The guidance in this section does not cover the release of N_2O from other processes, as these emissions are assumed to be negligible.

Equation 4.14b calculates N_2O emissions from blast furnace gas (BFG) and converter gas (LDG) flaring, considering that 20 percent of the BFG is removed from the production stream and then flared, and that all (100 percent) of the LDG is also flared (see Box 4.0).

EQUATION 4.14A (NEW)
N_2O EMISSIONS FROM FLARING (TIER 1)

BFG and LDG flaring:

$$\begin{aligned} E_{N_2O,\, non-energy} &= BFG \bullet R_{BFG\ flared} \bullet EF_{N_2O\ BGF\ flared} \\ &+ LDG \bullet R_{LDG\ flared} \bullet EF_{N_2O\ LDG\ flared} \end{aligned}$$

Where:

$E_{N_2O,\text{ non-energy}}$ = emissions of N_2O to be reported in IPPU Sector, tonne

BFG = blast furnace gas produced, tonne

LDG = converter gas produced, tonne

$R_{BFG\ flared}$ = rate of BFG removed from the production steam and then flared. If this data is not available, a default value of 0.2 can be assumed (see Box 4.0)

$R_{BFG\ flared}$ = rate LDG removed from the production steam and then flared. If this data is not available, a default value of 1.0 can be assumed (see Box 4.0)

$EF_{N2O\ BFG\ flared}$ = emission factor for BFG flared, tonne N_2O/tonne BFG produced

$EF_{N2O\ LDG\ flared}$ = emission factor for LDG flared, tonne N_2O/tonne LDG produced

The Tier 3 method uses plant specific emissions data or modelling results.

The total national emissions will equal the sum of emissions reported from each facility.

4.2.2.3 CHOICE OF EMISSION FACTORS

This section provides default emission factors for CO_2 and CH_4 to be used in Tier 1a and provides a discussion on carbon contents to be used in the carbon balance approach at higher Tiers.

TIER 1A METHOD

Carbon dioxide emission factors

Tables 4.1, 4.1a, 4.1b provide default emission factors for coke, sinter, pellet, iron and steel production from direct emission sources. The emission factors for the three steelmaking methods are based on measurements and expert judgment using typical practice for the different steel production scenarios.

Table 4.1 includes CO_2 emission factors for both coke production technology types, i.e. *with* and *without* by-product recovery. In the first case, the CO_2 EF 0.51 t CO_2/t coke was calculated as the mean value from the wide range of sources analysed and chosen to be the Tier 1 EF as a conservative factor, not comprising energy saving technologies, such as Coke Dry Quenching (CDQ), Coal moisture control etc. If these energy efficiency technologies are in use at a country´s coke plants, the inventory compiler may choose a lower EF, e.g. 0.30 t CO_2/t coke. The wide range for by-product recovery coke plants, whose variability reflects not only different operational and maintenance practices, but also, and foremost, the types of fuels used as primary for coke production (including different combinations of coal, natural gas, fuel oil, coke oven gas, converter or blast furnace gas and other fuels).

TABLE 4.1 (UPDATED)
TIER 1 DEFAULT CO_2 EMISSION FACTORS FOR COKE PRODUCTION

Process	Emission Factor	Source
Coke production using by-product recovery technology (tonne of CO_2/tonne of coke)	0.51	- (EU IPPC BREF 2013), Table 5.2, p.224 (0.16-0.86 t CO_2/t coke) - (Official Journal of the European Union 2011) (0.286 t CO_2/ t coke) - (Fruehan et al. 2000), Table A-10, p.33 (0.3-0.34 t CO_2 /t coke) - (US EPA 2012), section D.2.5, p.D-9 (0.21 tCO_2/ t coke) - (Zhang et al. 2012), Table 4, p.2026 (0.518 t CO_2 /t coke)
Coke production without by-product recovery (tonne of CO_2/tonne of coke)	1.23	- (US EPA 2012), section D.2.5, p.D-9

Table 4.1a includes CO_2 default emissions factor for sinter production, which represents the mean value based on the sources studied and refers to sinter plants which do not use carbonate ores. However, for those sinter plants which do use carbonate ores this CO_2 EF average can be up to twice as high. Moreover, this value can also vary widely depending on the kind of fuel gases used in the ignition oven.

For pellet production the scarce set of CO_2 EFs reported present a wide range of values. The default EF for Tier1 approach, included in Table 4.1.A, has been chosen as the maximum value reported. Similarly, for EAFs the CO_2 EF chosen corresponds to the maximum value reported.

TABLE 4.1A (NEW)
TIER 1 DEFAULT CO_2 EMISSION FACTORS FOR SINTER AND PELLET PRODUCTION

Sinter production (tonne of CO_2/tonne of sinter)	0.21	- (Fruehan et al. 2000), Table 4.1 (0.17-0.19 t CO_2/t sinter) - (Zhang et al. 2012), Table 4, p.2026 (0.21 t CO_2/t sinter) - (EU IPPC BREF 2013), Table 3.4, p.96 (0.162-0.368 t CO_2/t sinter) - (Official Journal of the European Union 2011) (0.171t CO_2/ t sinter)
Pellet production (tonne CO_2/tonne pellet produced)	0.19	- (EU IPPC BREF 2013), Chapter 4, Table 4.1, p.188

TABLE 4.1B (NEW)
TIER 1 DEFAULT CO2 EMISSION FACTORS FOR IRON AND STEEL PRODUCTION

Iron production (tonne CO_2/tonne of hot metal)	1.43	- (Fruehan et al. 2000), Table A-11, p. 33 (1.447-1.559 t CO_2/t hot metal) - (Zhang et al. 2012), Table 4, p. 2026 (1.375 t CO_2/t hot metal) - (Official Journal of the European Union 2011), Annex 1, (1.328 t CO_2/t hot metal)
Direct Reduced Iron production (tonne CO_2 per tonne DRI produced)	0.70	Direct Reduced Iron Production: European IPPC Bureau (2001), Integrated Pollution Prevention and Control (IPPC) Best Available Techniques Reference Document on the Production of Iron and Steel, December 2001, Table 10.1 Page 322 and Table 10.4 Page 331 http://eippcb.jrc.es/pages/FActivities.htm
Steelmaking Method		
Electric Arc Furnace (EAF) (tonne CO_2/tonne of steel produced) [1]	0.18	- (EU IPPC BREF 2013), Chapter 8, Table 8.1, p.429 (0,072-0,180 t CO_2/t of steel produced)
Basic Oxygen Furnace (BOF) (tonne CO_2/tonne of steel produced) [2,3]	1.58	- (Fruehan et al. 2000), Table A-11, p.33. Comparison of theoretical minimum and actual CO_2 emissions for selected processes comes up with a range of 0.189-0.207 t CO_2/t liquid steel, without considering blast furnace emissions - (Joint Research Center 2013), Table 7.3, p.369 (22.6-174 kg CO_2/t liquid steel), without considering blast furnace emissions
Open Hearth Furnace (OHF) (tonne CO_2 per tonne of steel produced) [2,4]	1.72	Steel Production: Consensus of experts and IISI Environmental Performance Indicators 2003 STEEL (International Iron and Steel Institute, 2004)

[1] The emission factor for EAF steelmaking does not include emissions from iron production. This factor is based on production of steel from scrap metal, and therefore the EAF emission factor does not account for any CO_2 emissions from blast furnace iron making. Therefore is not applicable to EAFs that use pig iron as a raw material.

[2] The emission factors for BOF and OHF steelmaking do include emissions from blast furnace iron production, and are consistent with Equation 4.4

[3] The emission factors for BOF represents the mean value of (Blast Furnace + BOF) CO_2 emissions across the sources studied.

Methane emission factors

Default CH_4 emission factors are provided in Table 4.2 below.

Table 4.2 (Updated)
Tier 1 default CH_4 emission factors for coke production (non fugitives), iron and steel production

Process	**Emission Factor**	**Source**
Coke Production (kg CH_4/tonne of coke produced)	0.089	- (Japan NIR 2018) (0,089 kg CH4/t coke produced), - (Joint Research Center, 2013), Chapter 5, Table 5.2, p.224 (0,001- 0,080 kg CH4/t coke produced)
Sinter Production (kg CH_4/tonne of sinter produced)	0.07	EMEP/CORINAIR Emission Inventory Guidebook (EEA, 2005). Processes With Contact: *Sinter and Pelletizing Plants: Sinter and Pelletizing Plants (Except Combustion 030301)* Table 8.2a Emission factors for gaseous compounds
DRI Production kg CH_4/TJ (on a net calorific basis)	1	Energy Volume default emission factor for CH_4 Emissions from natural gas combustion. [See Table 2.3 of Volume 2, Chapter 2.]

Nitrous oxide

Due to the absence of emission factor values reported in literature, the approach described in US CRF 2018 (Title 40, Chapter I, Subchapter C, Part 98, Subpart W), that estimate N_2O emission factors on the basis of CO_2 emission factors, is adopted. N_2O emission factors estimated on the basis of this approach, are provided in Table 4.2b below.

Table 4.2b (New)
Tier 1 default N_2O emission factors for coke production and iron and steel production

Process	**Emission Factor**	**Source**
Blast furnace gas flaring tonnes N_2O / tonnes BFG flared	1.4 E-06	$(EF_{N_2O})_{BFG\ flaring} = (EF_{CO_2})_{BFG\ flaring} \bullet \left[\left(\frac{EF_{N_2O}}{EF_{CO_2}}\right)_{Oil\ and\ gas\ production}\right]$ $(EF\ CO_2)_{BFG\_flaring}$ = 0.125 tonnes CO_2/ tonnes BFG produced, (equation 4.8a, with CC_{BFG} from Table 4.3) $^{(1)}$ Unit conversion made with 2.47 GJ/tonne of BFG
Blast furnace gas flaring tonnes N_2O / GJ BFG flared	5.6 E-07	
Converter gas flaring tonnes N_2O / tonnes LDG flared	2.8 E-06	$(EF_{N_2O})_{LDG\ flaring} = (EF_{CO_2})_{LDG\ flaring} \bullet \left[\left(\frac{EF_{N_2O}}{EF_{CO_2}}\right)_{Oil\ and\ gas\ production}\right]$ $(EFCO_2)$ LDG_flaring = 0.257 tonnes CO_2/ tonnes LDG produced, (equation 4.8a, with CC_{LDG} from Table 4.3)^1 Unit conversion made with 7,06 GJ/tonne of LDG
Converter gas flaring tonnes N_2O / GJ LDG flared	4.0 E-07	
$^1EF_{CO2}$ and EF_{N2O} for oil and gas production are set as 3.0 E-03 and 3.3 E-08 Gg gas per 10^6 m^3 gas produced, taken from Table 4.2.4.G IPCC 2019 Refinement.		

TIER 1B AND TIER 2 METHODS

The default carbon contents in Table 4.3 should be used if there is no information on average country specific carbon contents. Carbon contents in Table 4.3 are based on expert judgment, complementing those provided in Table 1.2 and 1.3 in Chapter 1 Volume 2 of the *2006 IPCC Guidelines*. It is a *good practice* to use country-specific values, based on measurements or other well-documented data. The Emission Factor Database (EFDB) provides a variety of well-documented emission factors and other parameters that may be better suited to national circumstances than the default values, although the responsibility to ensure appropriate application of material from the database remains with the inventory compiler.

TIER 3 METHODS

The Tier 3 method is based on aggregated plant-specific emission estimates or the application of the carbon balance approach at the plant specific level. The inventory compiler should ensure that each facility has documented the emission factors and carbon contents used, and that these emission factors are representative of the processes and materials used at the facility. The Tier 3 method requires carbon contents and production/consumption mass for all process materials and off-site transfers such as those listed in Table 4.3. While this Table provides default carbon contents, it is *good practice* under Tier 3 to adjust these values to reflect variations at the plant level. The carbon contents listed in Table 4.3 are only appropriate for the Tier 3 method if plant-specific information indicates that they correspond to actual conditions. It is anticipated that for the Tier 3 method the plant-specific data would include both carbon content data and production/consumption mass rate data, and that therefore the default values in Table 4.3 would not be applied to the Tier 3 method in most instances.

TABLE 4.3 (UPDATED)
TIER 2 MATERIAL-SPECIFIC CARBON CONTENTS FOR IRON AND STEEL PRODUCTION (TONNES C/TONNE)

Process Materials	Carbon Content
Blast Furnace Gas	0.17
Charcoal*	0.91
BF injection coal	0.806
Steam coal (combustion coal)	0.671
Coal Tar	0.62
Coke	0.83
Coke Oven Gas	0.47
Coking Coal	0.73
Direct Reduced Iron (DRI, Gas-based)	0.020
Direct Reduced Iron (DRI,Coal-based)	0.020
Dolomite/Crude dolomite	0.13
EAF Carbon Electrodes[1]	1.00
EAF coal	0.89
Heavy oil	0.793
Light oil	0.709
Kerosene	0.858
LPG	0.814
Hot Briquetted Iron [2]	0.02
Limestone	0.121
Natural Gas	0.73
Oxygen Steel Furnace Gas or Converter gas	0.35
Petroleum Coke [2]	0.87
Purchased Pig Iron	0.047
Scrap Iron [2]	0.04
Steel Scrap and Steel[2]	0.01

Note:

1 Assuming 80 percent petroleum coke and 20 percent coal tar

2 Source: ISO14404-1 & ISO14404-2 with conversion from CO_2 to C (multiplied by 12,011/44,01 as World Steel Association calculates in the table 4).

* The amount of CO_2 emissions from charcoal can be calculated by using this carbon content value, but it should be reported as zero in national greenhouse gas inventories. (See Section 1.2 of Volume 1)

4.2.2.4 CHOICE OF ACTIVITY DATA

TIER 1 METHOD

The Tier 1 method requires only the amount of steel produced in the country by process type, the total amount of pig iron produced that is not processed into steel, and the total amount of coke, direct reduced iron, pellets, and sinter produced; in this case the total amount of coke produced is assume to be produced in integrated coke production facilities. These data may be available from governmental agencies responsible for manufacturing statistics, business or industry trade associations, or individual iron and steel companies. If a country only has aggregate data available, a weighted factor should be used. Total crude steel production is defined as the total output of usable ingots, continuously-cast semi-finished products, and liquid steel for castings.

TIER 2 METHOD

The Tier 2 method requires the total amount of iron and steel, coke oven gas, blast furnace gas, and process materials such as limestone used for iron and steel production, direct reduced iron production, and sinter production in the country, in addition to onsite and offsite production of coke. These data may be available from governmental agencies responsible for manufacturing or energy statistics, business or industry trade associations, or individual iron and steel companies. These amounts can then be multiplied by the appropriate default carbon contents in Table 4.3 and summed to determine total CO_2 emission from the sector. However, activity data collected at the plant-level is preferred (Tier 3). If this is not a *key category* and data for total industry-wide reducing agents and process materials are not available, emissions can be estimated using the Tier 1 approach.

TIER 3 METHOD

The Tier 3 method requires collection, compilation, and aggregation of facility-specific measured emissions data or facility-specific process material production/consumption mass data and carbon content data. The Tier 3 method can be based on a plant-specific mass balance approach (for CO_2 emissions) or on plant-specific direct emissions monitoring data (for both CO_2 and CH_4 emissions). In this case, it is a *good practice* to apply a QA/QC for the monitoring data, following the recommendations included in Chapter 6 Volume 1 of the *2019 Refinement*. The Tier 3 method also may require activity data to be collected at the plant level and aggregated for the sectors. The plant-specific data should preferably be aggregated from data furnished by individual iron and steel and coke production companies. The amounts of process materials are more accurately determined in this manner. These data may also be available from governmental agencies responsible for manufacturing or energy statistics, or from business or industry trade associations. The appropriate amounts can then be multiplied by facility specific carbon content data and summed to determine total CO_2 emissions from the sectors, and the total emissions will be more accurate than when using the Tier 2 method. This approach also allows for additional accuracy by allowing individual companies to provide more accurate plant-specific data and/or to use more relevant carbon contents that may differ from the default factors used in Tier 2 method.

4.2.2.5 COMPLETENESS

RELATIONSHIP TO THE ENERGY SECTOR

Iron and steel production consists of many production processes (occurring at different facilities), such as coking, sintering, iron-making, blast furnace steelmaking and rolling. These processes are connected to each other with the pipeline network which carries by-product gases, such as coke oven gas, blast furnace gas and basic oxygen furnace gas. This complexity creates the risk of double counting of emissions or omission of emissions. Additionally, when there are many different types of steelworks in a particular country, it may be difficult to calculate CO_2 emissions for the Energy Sector and the Industrial Processes Sector separately without ambiguities.

Because of the dominant role of coke, it is important to consider the existence of coke making at a facility and define the boundary limits of the carbon balance at an iron and steelmaking facility to assure that CO_2 emissions are not double-counted. The combustion emissions from fuels obtained directly or indirectly from the feedstock for an IPPU process will normally be allocated to the part of the source category in which the process occurs (see Box 1.1 Chapter 1 Volume 3 of the *2006 IPCC Guidelines*). Following this criterion, the emissions from iron and steel production for the case of an integrated iron and steel plant should be reported under IPPU or under Energy, as shown in Figure 4.8a. Note in particular:

- The emissions from the combustion of blast furnace gas, coke oven gas and converter gas for sintering in the blast furnace and for steel making should be reported under IPPU.
- The emissions from the combustion of blast furnace gas, coke oven gas and converter gas to produce heat for different uses within the steelworks (rolling mill, hot rolling mill, plate mill, bar mill, cold rolling mill, coating, pipe) should be reported under IPPU.
- The emissions from the combustion of derived gases (including blast furnace gas, coke oven gas and converter gas) to produce electricity in an internal power plant should be reported under IPPU
- Consistent with the guidance in Box 1.1. Chapter 1 Volume 3 of the *2006 IPCC Guidelines*, where the derived gases are exported off-site for subsequent combustion at another facility, (for example a nearby brick works for heat production or a main electricity producer) then the emissions are reported in the appropriate source subcategories (1A2f or 1A1a).

- The emissions from flaring or venting of gases at coke ovens are allocated to the Energy (Fugitives) section 4.3.2.2 Chapter 4 Volume 2 of the *2019 Refinement*, whilst the emissions from flaring or venting of gases elsewhere in the Iron and Steel industry (e.g. blast furnace, sinter plant, basic oxygen furnace) are reported under IPPU.

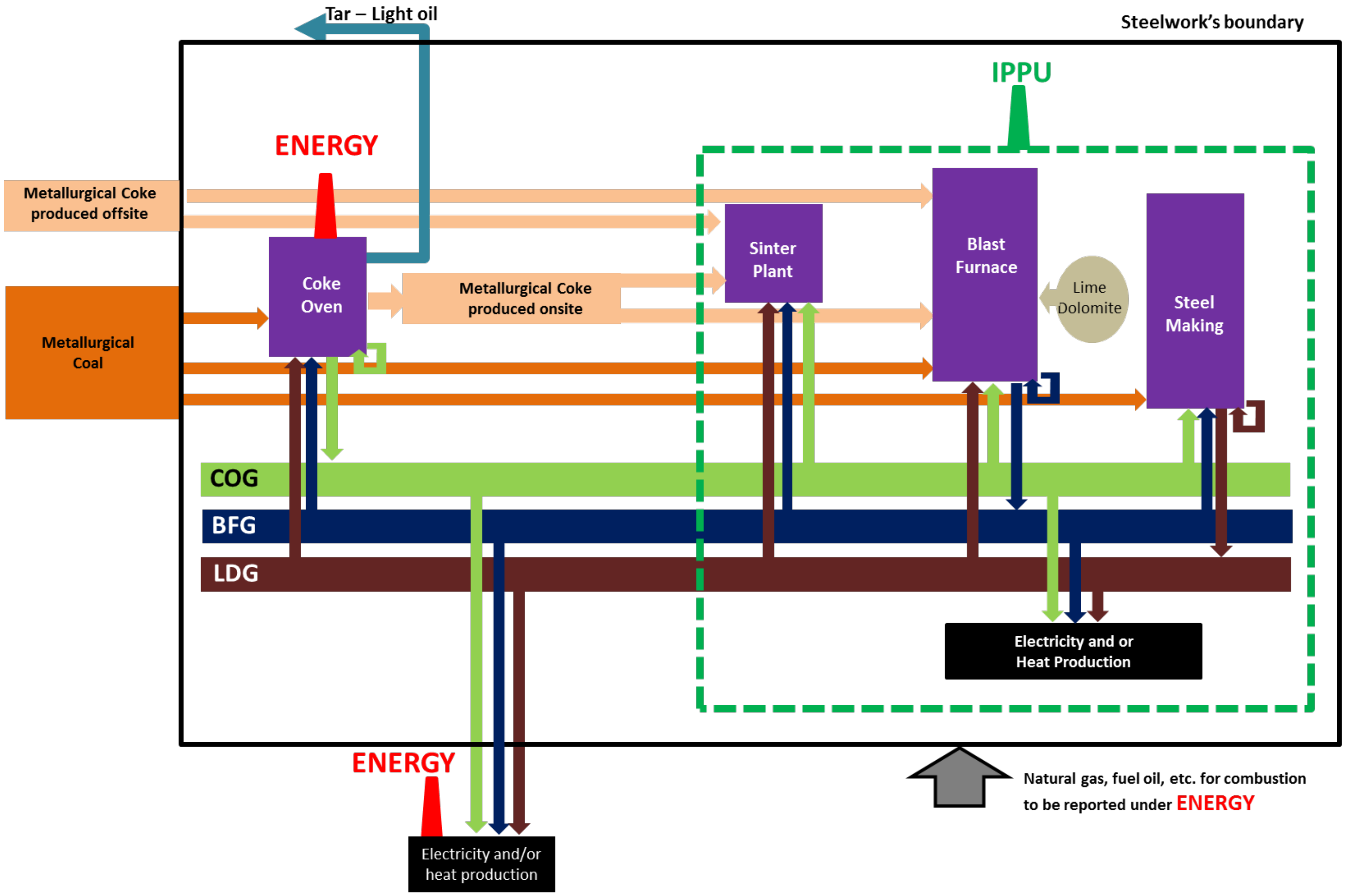
To avoid double counting and to ensure completeness it is a *good practice* to cross-check the proper allocation of the emissions between the Energy and IPPU sectors, and to document where and how they are reported in the inventory.

RELATION TO OTHER METHODOLOGICAL APPROACHES

In the iron and steel industry there has been a global effort to establish a common methodology for the calculation of CO_2 emissions and the energy intensity of steelworks as well as to conduct continuous data collection with the purpose of performance tracking and promoting international cooperation in reducing CO_2 emissions. The World Steel Association established the first method of this kind in 2007, and since then, has conducted yearly confidential CO_2 data collection form steelworks across the world. The method was refined further and was established as ISO 14404 "Calculation method of carbon dioxide emission intensity from iron and steel production" in 2013. This methodology is appropriate for CO_2 and energy management in the steel industry, and it is in line with national policies of many governments. The calculation method establishes clear boundaries for the collection of CO_2 emissions data (Reference ISO 14404 "Calculation method of carbon dioxide emission intensity from iron and steel production"). The net CO_2 emissions and production from a steel plant are calculated using all the parameters within the boundaries. The CO_2 emission intensity is calculated as the net CO_2 emission from the plant using the boundaries divided by the amount of crude steel produced by the plant. With this methodology, the CO_2 emission intensity of steel plants is calculated irrespective of the type of process used, products manufactured and geographic characteristics. This calculation method only uses primary inputs to the plant and primary outputs from the plant that are commonly measured and recorded by the plants; thus, the method requires neither the measurement of the specific efficiency of individual equipment or processes nor dedicated measurements of the complex flow and recycling of materials and waste heat. In this way, the calculation method ensures its simplicity and universal applicability without requiring steel plants to install additional dedicated measuring devices or to collect additional dedicated data other than those commonly used for plant management. Although the World Steel Association does not recommend using these calculations to determine the benchmark for free allocation under emissions trading schemes (because different regions have different energy sources and raw materials available), the calculations can be used to compare the performance of steel plants globally and to help plant staff determine their own position in energy and CO_2 efficiency

There is a difference between the *2019 Refinement* and ISO 14404 "Calculation method of carbon dioxide emission intensity from iron and steel production", dealing with the allocation of CO_2 emissions to the IPPU and Energy sectors, as in ISO 14404 the emissions from coking, sintering, blast furnacing, direct reduction, coke making processes, reheating furnaces and rolling are reported under Energy, and only the emissions from the use of limestone and dolomite are reported under IPPU.

Figure 4.8d (New) **Energy or IPPU CO_2 emissions allocation in an integrated iron and steel facility**



OTHER FORMS OF CARBON

Although the dominant means of producing crude iron, or pig iron, is blast furnacing using coke, other forms of carbon (e.g., pulverized coal, coal derivatives, recycled plastics or tires, natural gas, or fuel oil) can also be used to substitute for some portion of the coke in the blast furnace. In these cases, the materials should be accounted for as process sources of carbon in the same manner as coke, and care should be taken to deduct these materials from any general energy statistics, if they are included there. Iron can also be produced in other types of iron-making processes besides blast furnacing, such as direct reduced iron processes, often using natural gas or coal instead of coke, and these carbon sources should be accounted for in the same manner as coke, as they serve the same purpose.

In most blast furnaces, the iron making process is aided by the use of carbonate fluxes (limestone or dolomite). Because these materials are necessary raw materials for the process, they should be accounted for as part of the iron and steelmaking inventory. Again, however, care should be taken not to double-count emissions associated with limestone and dolomite usage if accounted for separately in the minerals sector. (See Section 2.5, Other Process Uses of Carbonates, in this volume.)

SINTER

Some integrated facilities also utilize sinter plants to convert iron-bearing fines into an agglomerate (or sinter) suitable for use as a raw material in the blast furnace. Typically, coke fines (or coke breeze) are used as a fuel in the sintering process and are a source of CO_2 and CH_4 emissions. If the coke fines are produced at a coke plant within the facility and the CO_2 and CH_4 emissions are accounted for in the coal entering the facility, or if the coke breeze is otherwise accounted for as purchased coke, the CO_2 and CH_4 emissions from coke used in sintering should not be double-counted. Emissions from sinter production are categorised as IPPU emissions and should be reported as such.

EXHAUST GASES

It is important to avoid double counting blast-furnace-derived by-product gases such as blast furnace gas, or recovered converter off-gas, if they have been accounted for as process emissions. Process emissions should include all carbon inputs in the blast furnace, used as the primary reductant. In a typical fully integrated coke, iron and steel plant situation, adjustments may need to be made for coke oven by-products and the carbon content of shipped steel, which should be clearly mentioned in the description of the sources. In some cases, it may also be necessary to make adjustments for blast furnace gas or iron that may be sold or transferred off site. The process flow of exhaust gases is clearly illustrated in Figures 4.1-4.5.

The use of a default emission factor for CO_2 emission estimates with Tier 1a for metallurgical coke production and Tier 1 for iron and steel production assumes an average mix of fuel between coke oven gas, blast furnace gas and, in some cases, converter off-gas. On the other hand, the Tiers based on the carbon balance approach consider the actual flow of these gases used and produced. Therefore, the combined use of Tier 1a to estimate CO_2 from metallurgical coke production and Tier 2 or 3 to estimate CO_2 from iron and steel production in integrated plants can lead to double counting or underestimation of some of the gases used. Similarly, the combined use of Tier 1 to estimate CO_2 from iron and steel production and Tier 2 or 3 to estimate CO_2 from metallurgical coke production can lead to double counting or underestimation of some of the gases used. The inventory compiler should take this into consideration when choosing the Tiers to estimate CO_2 emissions from integrated iron and steel plants.

ELECTRODE CONSUMPTION

Electrode consumption amounts to about 3.5 kg/tonne for EAF furnaces. However, depending upon the characteristics of the charged materials, some carbon may be added to the EAF (typically about 20 kg/tonne) for process control purposes or may be contained in the charged materials themselves as iron substitutes, an increasingly more frequent trend. In these cases, CO_2 and CH_4 emissions from these additional carbon-bearing materials should be considered process-related and accounted for in the inventory because their carbon content is not as likely to have been accounted for elsewhere in the inventory. In addition, if natural gas is used to enhance reactions in an EAF as reducing agent it should be accounted for as a carbon source as all process materials used in iron and steel manufacturing are reported as IPPU emissions.

Some specialty steel production takes place in electric induction furnaces, in which case the charge is 100 percent steel scrap and where there are no carbon electrodes. There are no appreciable CO_2 or CH_4 emissions from this steelmaking process.

OHF PROCESS

Although the OHF is no longer prevalent, it may be necessary to inventory CO_2 and CH_4 emissions from this steelmaking process in some countries. An open hearth furnace is typically charged with both molten iron and scrap as in the case of a BOF, and oxygen is injected into the furnace, but reduction of carbon in the iron and melting of the charge also takes place by firing fossil fuels (e.g., natural gas, fuel oil, coal or tar) across the surface of the raw material bath. Carbon in the iron may be ignored, as in the case of the BOF, because it has been accounted for as a source of carbon for iron-making. However, carbon in the fuels used in the open hearth process should be accounted for as IPPU emissions.

4.2.2.6 DEVELOPING A CONSISTENT TIME SERIES

No refinement.

4.2.3 Uncertainty assessment

The default emission factors for coke production and iron and steel production used in Tier 1 may have an uncertainty of ± 10 percent. Tier 2 material-specific carbon contents would be expected to have an uncertainty of 10 percent. Tier 3 emission factors would be expected to be within 5 percent if plant-specific carbon content and mass rate data are available. Table 4.4 provides an overview of the uncertainties for emission factors, carbon contents and activity data.

TABLE 4.4 (UPDATED)
UNCERTAINTY RANGES

Method	Data Source	Uncertainty Range
Tier 1	CO_2 Default Emission Factors CH_4 Default Emission Factors N_2O Default Emission Factors National Production Data Material-Specific Default Carbon Contents	± 10% ± 400% ± 300% ± 10% ± 10%
Tier 2	Material Country Specific Carbon Contents National Reducing Agent & Process Materials Data	± 10% ± 10%
Tier 3	Company-Derived Process Materials Data Company-Specific Measured CO_2 and CH_4 Data Company-Specific Emission Factors	± 5% ± 5% ± 5%

4.2.4 Quality Assurance/Quality Control (QA/QC), Reporting and Documentation

No refinement.

4.3 FERROALLOY PRODUCTION

No refinement.

4.4 PRIMARY ALUMINIUM PRODUCTION

This sub-chapter 4.4 "Primary Aluminium Production" Chapter 4 Volume 3 of the *2019 Refinement* is an update of sub-chapter 4.4 Chapter 4 Volume 3 of the *2006 IPCC Guidelines* and should be used *instead of* the sub-chapter 4.4 in the *2006 IPCC Guidelines*, with two exceptions relating to accounting of CO_2 emissions from the primary aluminium smelting process:

- Section 4.4.2.1 – 'Choice of method for CO_2 emissions from primary aluminium production',
- Section 4.4.2.2 – 'Choice of emission factors for CO_2 emissions from primary aluminium production'.

For these two sections, the existing *2006 IPCC Guidelines* should be used. No refinements have been made to guidance on CO_2 emissions from primary aluminium smelting.

Updates and new guidance since the *2006 IPCC Guidelines* include the following:

- Section 4.4.1 is an updated introduction to GHG emissions from primary aluminium production, including alumina refining via alternative Bayer-Sinter and Nepheline technologies.
- Sections 4.4.2.3 to 4.4.2.7 and sections 4.4.3 to 4.4.4 provide new and updated guidance for accounting of perfluorocarbon (PFC) emissions from the primary aluminium smelting process.
    (i) Updated technology classes – addition of '$PFPB_L$', '$PFPB_M$', '$PFPB_{MW}$' – to replace the 'CWPB' class in existing *2006 IPCC Guidelines* for accounting PFC emissions only. For accounting of CO_2 emissions from primary aluminium smelting, the 'CWPB' class should still be used.
    (ii) Updated guidance (including updated Tier 1 and Tier 2 default factors and uncertainties) on PFC emissions from 'high voltage anode effects' (HVAE), previously termed 'anode effects' in the *2006 IPCC Guidelines*. This includes new Tier 2b and Tier 3b methods for estimating PFC emissions from HVAE, using *individual* anode effect durations, rather than overall anode effect performance. Existing methods based on *overall* anode effect performance have been relabelled as Tier 2a and Tier 3a.
    (iii) New guidance on PFC emissions from 'low voltage anode effects' (LVAE), using either default (Tier 1) or facility-specific (Tier 3) emission factors.
    (iv) New guidance on accounting PFC emissions during cell start-up (CSU) periods.
    (v) New guidance on Total PFC emissions, being the sum of HVAE, LVAE and CSU emissions (if applicable).
    (vi) A new Tier 3_{DM} facility-specific method for total PFC emissions by direct gas measurement.
    (vii) Corresponding updates relating to Time-Series Consistency, Uncertainty Assessment and QA/QC Reporting and Documentation sections.
- Sections 4.4.5 to 4.4.7 provide new guidance on accounting GHG emissions from alumina production via alternative refining processes: 'Bayer-sintering parallel' (BSP), 'Bayer-sintering sequential' (BSS) and 'Nepheline processing' (NP) processes:
    (i) This includes a Tier 1 and facility-specific Tier 3 method to account for CO_2 emissions for BSP, BSS and NP production routes.
    (ii) Note that no new guidance is required for the alumina production via the conventional 'Bayer' process.

4.4.1 Introduction to Primary Aluminium

This section covers emissions from primary aluminium production processes including, alumina refining using the Bayer-Sinter and Nepheline alternative refining technology[4]. A number of refinements and updates have been made to the *2006 IPCC Guidelines* and are detailed in the following sections.

Primary aluminium production typically begins with the mining of aluminium-containing ores (bauxites). Most bauxite is refined through the Bayer Process, which thermo-chemically extracts aluminium oxide (alumina) from the ore. The main sources of greenhouse gas emissions from the Bayer Process are covered by existing guidance in the *2006 IPCC Guidelines* for lime production (Volume 3, Section 2.3) and fossil fuel combustion associated with alumina hydrate calcination and heat production for hydrochemical processes (Volume 2: Energy). A small proportion of alumina (<3 percent in 2015) is produced from the Bayer-Sinter process or nepheline ore refining process using alternative technology. New guidance has been included in this chapter for emissions from sub-processes related to the Bayer-Sinter process and nepheline ore processes only.

Alumina is reduced to molten aluminium metal via the electrolytic Hall-Héroult process. In this process, electrolytic reduction cells can differ in the form and configuration of the carbon anode and alumina feed system and are typically grouped by technology accordingly. In the *2006 IPCC Guidelines*, four technology types were defined, representing the technology in place at the time (percent global production): Centre-Worked Prebake – *CWPB* (82 percent including Point-Fed Prebake, *PFPB*), Side-Worked Prebake – *SWPB* (2 percent), Horizontal Stud Søderberg – *HSS* (3 percent) and Vertical Stud Søderberg – *VSS* (13 percent).

Since 2006, the technological landscape has changed, a result of the closure of older technology facilities and significant investment in new, larger state-of-the-art facilities. Point-Fed Prebake Technology for example has increased from <80 percent share of global production in 2006 to >90 percent in 2017 but more significantly, the growth in technology without fully automated anode effect intervention strategies for PFC GHG emissions has risen from <30 percent of global production in 2006 to >60 percent in 2017. As such, the technology types have been redefined as follows:

(i) *Legacy Point-Fed Prebake (PFPB$_L$)* – older cell designs with line currents of less than 350kA;
(ii) *Modern Point-Fed Prebake (PFPB$_M$)* – new cell technologies[5] that operate at line currents in excess of 350kA including: AP3X/AP4X, APXe/AP60, EGA DX and DX+;
(iii) *Modern Point-Fed Prebake without fully automated anode effect intervention strategies for PFC emissions (PFPB$_{MW}$)* – new cell technologies operating with large cells with line currents often in excess of 350kA, with no automatic anode effect intervention capacity (refer to Box 4.1a description) or with non-standard HVAE definitions, i.e. where HVAEs are not counted until the cell voltage has exceeded the threshold for 15 to as many as 120 seconds (Marks & Nunez 2018b; Wong *et al.* 2018) vs. 3 seconds for the rest of the industry (refer to Box 4.2 for typical definition);
(iv) *Side-Worked Prebake* (SWPB) technology;
(v) *Horizontal Stud Søderberg* (HSS) technology; and
(vi) *Vertical Stud Søderberg* (VSS) technology.

The three new Prebake technology classes – PFPB$_L$, PFPB$_M$ and PFPB$_{MW}$ – should be used for accounting of PFC emissions from primary aluminium smelting, in place of the previous CWPB class in the *2006 IPCC Guidelines*. However, for accounting CO_2 emissions from primary aluminium smelting, the previous CWPB class should still be used.

Although smelting technology has changed somewhat, the most significant process emissions have not. They are:

(i) CO_2 emissions from the consumption of carbon anodes in the reaction to convert aluminium oxide to aluminium metal (for which no refinements are included in this update for primary aluminium smelting);

(ii) Emissions of the PFCs, tetrafluoromethane (CF_4) and C_2F_6 during process upset conditions known as 'anode effects' (for which refinements for aluminium smelting are included in the following sections).

Also emitted are less significant process emissions: CO, Sulphur Dioxide (SO_2), and Non-Methane Volatile Organic Carbon (NMVOC). Sulphur hexafluoride (SF_6) is not emitted during the electrolytic process and is only

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[4] Emissions from the combustion of fossil fuels associated with primary aluminium production, bauxite mining, and aluminium production from recycled sources are covered in Volume 2: Energy. Also, carbon dioxide emissions associated with the production of electricity from fossil fuel combustion to produce aluminium are also covered in Volume 2.

[5] Details on some of these newest cell technologies are available on the following references: (Bardai *et al.* 2009; Rio Tinto Alcan 2013; Emirates Global Aluminium 2017)

rarely used when fluxing specialized, high magnesium aluminium alloys, from which small quantities can be released as fugitive emissions.

BOX 4.1A (NEW)
FULLY AUTOMATED ANODE EFFECT INTERVENTION STRATEGIES FOR PFC EMISSIONS

Many Point-Fed Prebake (PFPB) aluminium smelters employ fully automated control strategies to reduce PFC emissions, otherwise known as '*automatic anode effect intervention* or *termination*' strategies. These are strategies that rapidly terminate high voltage anode effects (HVAE) when they are detected, using both: (i) automated up/down movements of carbon anodes and (ii) automated feeding of alumina to rapidly increase dissolved alumina levels in the cell; in most cases, no manual intervention is required.

However, these automated strategies are not employed in one technology class – *Modern Point-Fed Prebake without fully automated anode effect intervention strategies for PFC emissions* ($PFPB_{MW}$) – where anode effects are terminated through manual operator intervention, which can result in higher PFC emissions. This technology class is also characterised by the use of HVAE definitions that differ significantly from that used in the rest of industry (see Box 4.2).

4.4.2 Methodological issues for primary aluminium production

4.4.2.1 CHOICE OF METHOD FOR CO_2 EMISSIONS FROM PRIMARY ALUMINIUM PRODUCTION

No refinement.

4.4.2.2 CHOICE OF EMISSION FACTORS FOR CO_2 EMISSIONS FROM PRIMARY ALUMINIUM PRODUCTION

No refinement.

4.4.2.3 CHOICE OF METHOD FOR PFCS

This section includes background and guidance on methods for estimating PFC emissions from different sources – 'high voltage anode effects' (HVAE) and low voltage anode effects (LVAE) – using a range of methods.

PFC EMISSIONS FROM ALUMINIUM PRODUCTION

During electrolysis, alumina (Al_2O_3) is dissolved in a fluoride melt comprising 80 percent by weight cryolite (Na_3AlF_6). Perfluorocarbons (PFCs) are formed from the reaction of the carbon anode with the cryolite melt during a process upset condition known as an 'anode effect' (see Box 4.2). An anode effect occurs when the concentration of alumina in the electrolyte is too low to support the standard anode reaction. When the *2006 IPCC Guidelines* were developed, anode effects were characterised by a sudden increase in voltage generally greater than 8V (US EPA 2008) for a period of approximately 3 seconds. These anode effects are now known as a 'high voltage anode effects' (HVAE), which release both CF_4 and C_2F_6.

BOX 4.2 (UPDATED)
HIGH AND LOW VOLTAGE ANODE EFFECT DESCRIPTION

An anode effect is a process upset condition where an insufficient amount of alumina is dissolved in the electrolyte, resulting in the emission of PFC gases. This often causes cell voltage to be elevated above the normal operating range. However, PFC gases can also be generated without elevated cell voltage.

A high voltage anode effect (HVAE) is typically identified as an anode effect where the voltage exceeds the specific voltage threshold defined at the facility for a specific duration. The typical voltage threshold of the industry, and used within this guideline, is 8 volts (Tabereaux 2004; US Environmental Protection Agency & International Aluminium Institute 2008) while the typical duration is 3 seconds (Wong *et al.* 2015).

A low voltage anode effect (LVAE) is typically identified as emission of PFC gases in cases where the cell voltage does not exceed the voltage threshold.

Since the late 2000s, driven by the development of more productive, high-amperage cell technology with many large anodes, 'low voltage anode effect' (LVAE) emissions of CF_4 have been identified. These LVAE emissions have been the focus of much research and occur as result of the same process upset condition as HVAE emissions but often at a smaller, localised scale. Guidance on estimating LVAE C_2F_6 emissions has not been provided here as C_2F_6 concentrations from LVAE are most of the time undetectable (within the noise level of the measuring instrument) or at low ppb levels. During LVAE, the cell voltage typically remains below the formation voltage of C_2F_6. Some research (Asheim *et al.* 2014; Dion *et al.* 2016) has even concluded that formation of C_2F_6 from LVAE does not occur, or occurs at levels so low, it is considered negligible.

LVAE emissions have not been included in national GHG inventories to date because the information and methodology for their estimation was not available, but estimates should now be included to ensure GHG inventories are as complete as possible.

CHOICE OF METHODOLOGIES FOR PFCS

It is *good practice* to estimate and report *Total PFC emissions*, i.e. the sum of HVAE and LVAE emissions combined. The decision trees shown in Figures 4.12 and 4.12a describe *good practice* in choosing the PFC inventory methodology appropriate for national circumstances for HVAE and LVAE, respectively. Table 4.14a provides a summary of all methods in this guidance for estimating PFC emissions at Tiers 1 to 3. Note that the methodologies for HVAE and LVAE are presented separately to allow for different Tiers to be adopted for each element if necessary.

All inventory compilers in countries with aluminium production should be able to implement at least the Tier 1 method and thereby ensure completeness of reporting. Although this chapter presents default emission factors, countries should make every effort to use higher Tier methods because emission rates can vary greatly, and the uncertainty associated with Tier 1 factors is very high. Most aluminium smelters routinely collect the process data needed for calculation of Tier 2 emissions factors. The sole exception is facilities with $PFPB_{MW}$ technology, whose process data (specifically, accounting of HVAEs) is not currently compatible with the Tier 2 emission factors presented here. For these smelters, it is still possible to implement Tier 3 methods – for example, production-based emission factors (for HVAE and LVAE emission sources, or total PFC emissions) or direct PFC gas measurements (Tier 3_{DM}). Furthermore, use of Tier 3 methods for HVAE emissions (based on HVAE performance) is also possible for $PFPB_{MW}$ facilities, provided conventional definitions of HVAEs (refer to Box 4.2) are adopted.

For HVAE emissions, the Tier 1 method is based on aluminium production, while the Tier 2 (2a and 2b) and Tier 3 ($3a_{HVAE}$ and $3b_{HVAE}$) methods are based on plant-specific process data for HVAEs, which are regularly collected by smelters. In choosing a method for estimating PFCs, it should be noted that the uncertainty associated with higher tier methodologies is generally significantly lower than that for Tier 1, and therefore it is generally *good practice* to use Tier 2 and Tier 3 methodologies if this is a *key category*. There is an exception for countries where the prevailing technology is $PFPB_{MW}$, whose current definitions (and therefore accounting) of HVAEs are not compatible with the Tier 2a, 2b, $3a_{HVAE}$, or $3b_{HVAE}$ methods in this guidance. In these cases, the Tier 1 method is acceptable for estimating emissions from HVAE even if the source is *key*, although use of Tier 3 methods (e.g. production-based facility-specific factors, or direct measurement Tier 3_{DM}) will significantly reduce uncertainty.

The Tier 3 methodologies for HVAE PFC emissions should be utilized with coefficients calculated from measurement data obtained using good measurement practices (US Environmental Protection Agency & International Aluminium Institute 2008). Communication with primary aluminium producers will determine the availability of process data, which, dictates the method used to calculate emissions. Plants other than $PFPB_{MW}$

routinely measure HVAE performance as ‘anode effect minutes per cell-day’. HVAE PFC emissions are directly related to anode effect performance via a coefficient specific to technology or plant.

In the *2006 IPCC Guidelines*, two methods for calculating coefficients for HVAE PFCs were outlined: slope and overvoltage. The overvoltage method is not widely used anymore so this update will focus on the slope method only. If the overvoltage method is still used, it should be adopted at the Tier 3 level only. If Tier 3 is not possible then it is *good practice* is to adopt the Tier 2a slope method.

For LVAE emissions, a Tier 1 method and two Tier 3 methods are provided. The Tier 1 method calculates PFC emissions by multiplying technology-specific default emission factors by aluminium production. The first Tier 3 method calculates PFCs by multiplying a facility-specific factor (ratio of LVAE to HVAE emissions, based on prior measurements) by the HVAE emissions (Marks & Nunez 2018b). This takes into account plant-specific performance at the HVAE level. The second Tier 3 method for LVAE uses a facility-specific, production-based emission factor for LVAE emissions. There is currently no generally recognised means to calculate LVAE CF_4 emissions from the process control data that is normally recorded during primary aluminium production. The most accurate approach to date is to directly measure both LVAE and HVAE PFC emissions at the individual facility level (Tier 3_{DM} methodology for total PFC emissions), but this is not widely or regularly practiced by industry. Moreover, there is currently no official methodology to standardise the measurement of LVAE PFC emissions. Until an official methodology is released, the ‘Protocol for Measurement of CF_4 and Hexafluoroethane (C_2F_6) Emissions from Primary Aluminium Production’ ((US Environmental Protection Agency & International Aluminium Institute 2008) can be used as guidance for total emissions measurement. It should be noted that there is ongoing work within industry to provide an updated measurement protocol. The LVAE methodologies proposed here provide a first step towards total emissions reporting but inventory compilers should be aware of the very high level of uncertainty that accompanies these estimates and that work is ongoing within the aluminium industry to provide *good practice guidelines* to complement these methodologies. It is *good practice* to check the EFDB as a source for future LVAE factors.

PFC emissions can also occur during cell start-up (CSU) – refer to Box 4.3 for a description. If they are not already included in normal HVAE and LVAE accounting, then HVAE emissions during cell start-up can be estimated via a Tier 2 approach ($2b_{HVAE}$ methodology, based on individual anode effect durations) or a Tier 3 approach using facility-specific emission factors or coefficients (Tier $3a_{HVAE}$, $3b_{HVAE}$ or 3_{CSU}).

For all facilities, the Tier 3 approach is preferred because plant-specific coefficients will lead to estimates that are more accurate. If no PFC measurements have been made to establish a plant-specific coefficient, the Tier 2 method can be used until measurements have been made and Tier 3 coefficients are established. Countries can use a combination of methodologies depending on the type of data available from individual facilities.

ACCOUNTING FOR ALL SOURCES OF PFC EMISSIONS

In the following sections, a number of different methodologies with differing levels of uncertainty are proposed to estimate PFC emissions. To obtain the total respective emissions of CF_4 and C_2F_6, the various sources of PFC should be summed using Equation 4.24a. This equation is applicable for estimating total PFC emissions for all Tier methods – the only exception being Tier 3_{DM} direct gas measurement as this already provides total PFC emissions from all sources.

EQUATION 4.24A (NEW)
TOTAL PFC EMISSIONS

$$Total\ E_{CF_4} = (HVAE\ E_{CF_4} + LVAE\ E_{CF_4} + CSU\ E_{CF_4})$$

and

$$Total\ E_{C_2F_6} = (HVAE\ E_{C_2F_6} + CSU\ E_{C_2F_6})$$

Where:

Total E_{CF4} = Total CF_4 from aluminium production, kg CF_4

Total E_{C2F6} = Total C_2F_6 from aluminium production, kg C_2F_6

HVAE E_{CF4} = HVAE emissions of CF_4 from aluminium production, kg CF_4

HVAE E_{C2F6} = HVAE emissions of C_2F_6 from aluminium production, kg C_2F_6

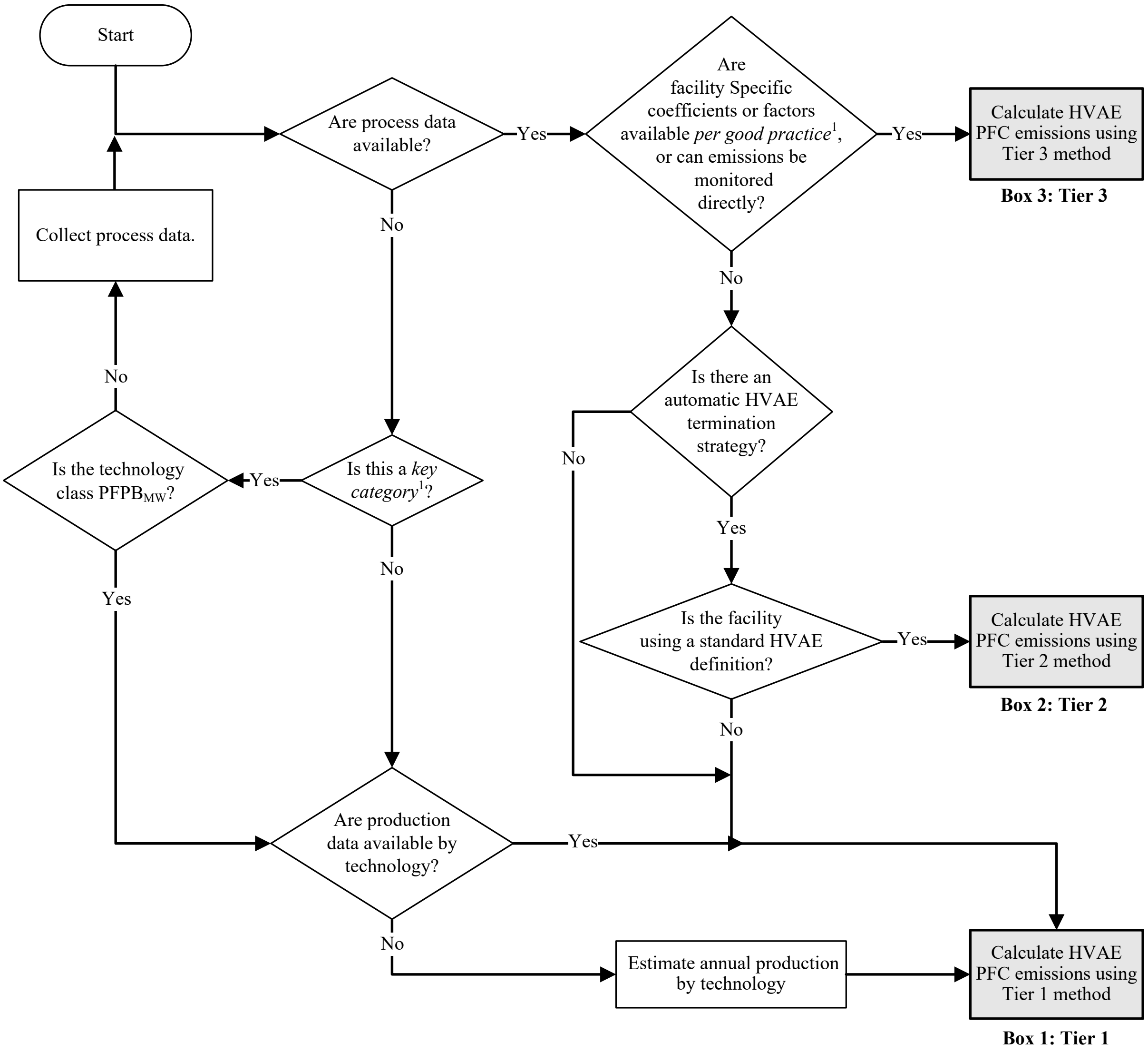
LVAE E_{CF4} = LVAE emissions of CF_4 from aluminium production, kg CF_4

CSU E_{CF4} = Total amount of CF_4 produced during cell start-ups for a specific period, kg CF_4

CSU E_{C2F6} = Total amount of C_2F_6 produced during start-ups for a specific period, kg C_2F_6

Note that the last terms in Equation 4.24a, CSU E_{CF4} = 0 and CSU E_{C2F6} = 0, where cell start-up emissions are already accounted for by normal accounting of HVAE and LVAE emissions. Care should be taken neither to omit nor to double count emissions from cell start-ups.

Figure 4.12 (Updated) Decision tree for calculation of HVAE related PFC emissions from primary aluminium production

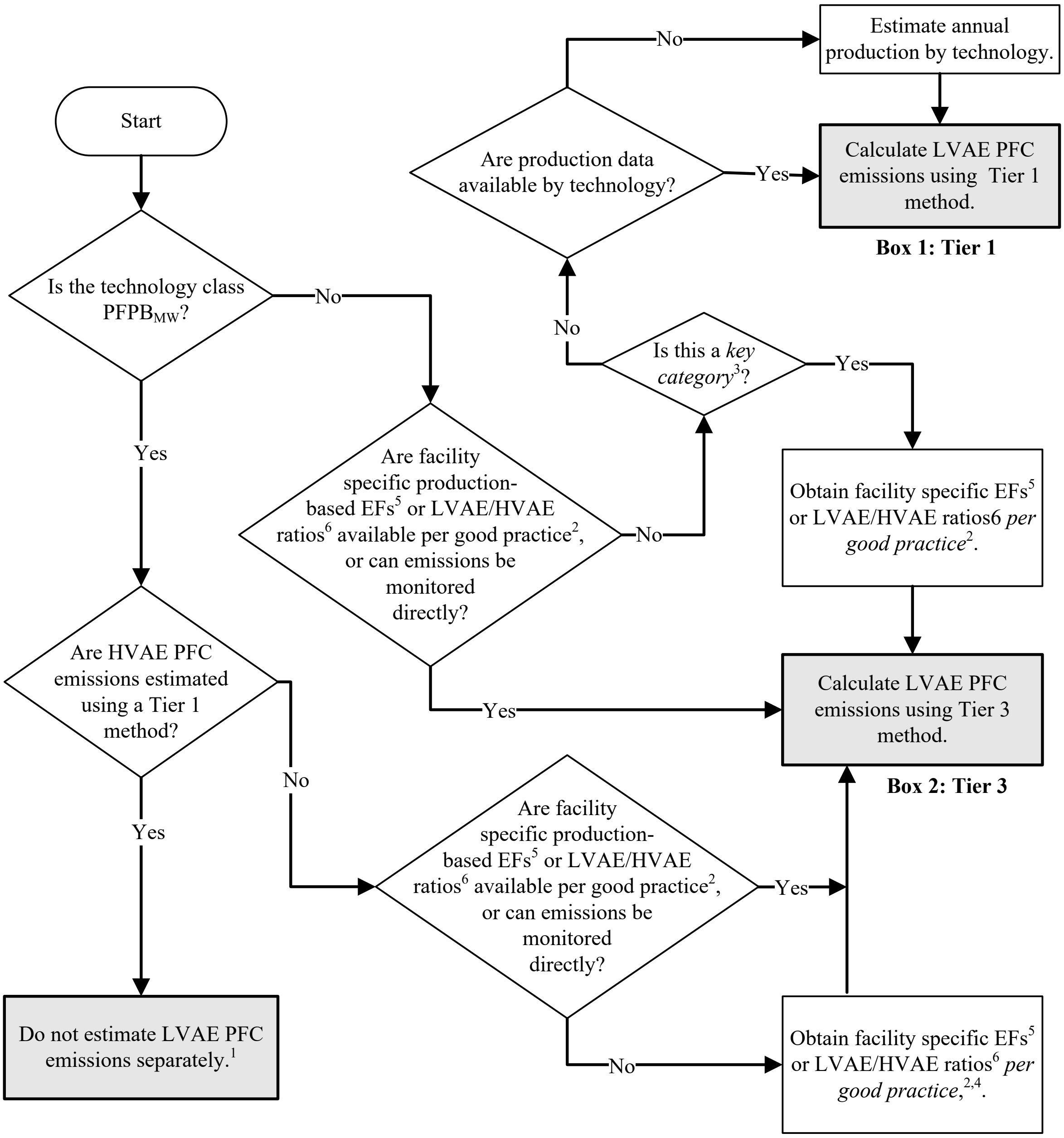


Notes:

[1] *Good practices* for obtaining facility specific PFC emission coefficients are detailed in the Protocol for Measurement of Tetrafluoromethane (CF_4) and Hexafluoroethane (C_2F_6) Emissions from Primary Aluminum Production (US Environmental Protection Agency & International Aluminium Institute 2008).

[2] 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.

Figure 4.12a (New) Decision tree for calculation of LVAE related PFC emissions from primary aluminium production



Notes:

[1] LVAE PFC emissions are already accounted for in the Tier 1 default HVAE EF for $PFPB_{MW}$.

[2] *Good practices* for obtaining facility specific PFC emission coefficients are detailed in the Protocol for Measurement of Tetrafluoromethane (CF_4) and Hexafluoroethane (C_2F_6) Emissions from Primary Aluminium Production (US Environmental Protection Agency & International Aluminium Institute 2008).

[3] 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.

[4] Any $PFPB_{MW}$ facilities employing facility-specific coefficients for HVAE emissions are likely to have the necessary data to obtain facility-specific coefficients or ratios for LVAE emissions.

[5] To use the facility-specific *production-based EF* method (Equation 4.27c), metal production data from the facility must be available.

[6] To use the facility-specific *LVAE/HVAE ratio* method (Equation 4.27d), HVAE emissions must be estimated first.

Table 4.14a (New)
Summary of accounting methods for PFC emissions

Tier		Emission Source	PFC Gas	Method Description	By	Cell Technology Applicable
1	1_{HVAE}	HVAE	CF_4, C_2F_6	Production-based default emission factor	Technology class	All technologies
	1_{LVAE}	LVAE	CF_4	Production-based default emission factor	Technology class	All technologies
2	2a HVAE	HVAE	CF_4, C_2F_6	Slope method[a,f]	Technology class	All technologies[d] *except* $\mathrm{PFPB}_{\mathrm{MW}}$
	2b HVAE	HVAE	CF_4, C_2F_6	Non-linear method[b,c]	Technology class	$\mathrm{PFPB}_{\mathrm{M}}$, $\mathrm{PFPB}_{\mathrm{L}}$ and SWPB only
3	3a HVAE	HVAE	CF_4, C_2F_6	Slope[a] or Overvoltage[e] method[g]	Facility specific	All technologies[d]
	3b HVAE	HVAE	CF_4, C_2F_6	Non-linear method[b]	Facility specific	All technologies[d]
	3_{LVAE}	LVAE	CF_4	LVAE/HVAE ratio or production-based factor	Facility specific	All technologies
	3_{CSU}	CSU	CF_4, C_2F_6	Cell start-up emission factor	Facility specific	All technologies
	3_{DM}	Total	CF_4, C_2F_6	Direct gas measurement[h]	Facility specific	All technologies

Notes:

[a] The slope method is where HVAE emissions are estimated based on *overall* anode effect performance.

[b] Non-linear methods refer to the Tier 2b or 3b (Marks & Nunez 2018a) and (Dion *et al.* 2018a) methods, where HVAE emissions are estimated based on *individual* anode effect measurement.

[c] Tier 2b methods for HVAE emissions are only applicable for $\mathrm{PFPB}_{\mathrm{M}}$, $\mathrm{PFPB}_{\mathrm{L}}$ and SWPB technologies; alternative methods should be used for VSS, HSS and $\mathrm{PFPB}_{\mathrm{MW}}$ technologies.

[d] The Tier 2a/3a and 2b/3b methods for HVAE emissions are *not* applicable for $\mathrm{PFPB}_{\mathrm{MW}}$ technology, due to inconsistencies in defining an HVAE. However, if consistent definitions (refer to Box 4.2) are adopted, then use of Tier 3a or 3b for $\mathrm{PFPB}_{\mathrm{MW}}$ technology is possible.

[e] The overvoltage method is an alternative to the slope method, where HVAE emissions are estimated based on *overall* anode effect performance; however this method should only be adopted a Tier 3 facility-specific level, since Tier 2 default emission coefficients have not been updated here in the *2019 Refinement*.

[f] Use of the Tier 2a slope method for HVAE emissions during cell start-up (CSU) periods is possible, however, this may lead to overestimates of emissions.

[g] To use the Tier 3a method for CSU emissions, it is *good practice* to use individual facility slope or overvoltage coefficients specifically for cell start-ups (as opposed to coefficients for normal operations, which may result in overestimates of emissions).

[h] The Tier 3_{DM} direct gas measurement method at individual facilities provides emission measurements that are inclusive of HVAE and LVAE emissions during normal operations as well as CSU emissions (during cell start-up).

ESTIMATING EMISSIONS FROM HIGH VOLTAGE ANODE EFFECTS

Tier 1 method for High Voltage Anode Effect (HVAE) emissions: Use of technology-based default emission factors

The Tier 1_{HVAE} method uses technology-based default emission factors for the main production technology types (Legacy PFPB, Modern PFPB, Modern $\mathrm{PFPB}_{\mathrm{MW}}$, SWPB, HSS and VSS). PFC emissions can be calculated according to Equation 4.25. The level of uncertainty in the Tier 1 method is much greater because individual facility anode effect performance, which is the key determinant of anode effects and thus PFC emissions, is not directly taken into account. Tier 1 can be consistent with *good practice* when PFCs from primary aluminium is not a *key category*, when pertinent process data are not available from operating facilities.

Tier 1 can also be consistent with *good practice* when the cell technology is $\mathrm{PFPB}_{\mathrm{MW}}$ as the process data required for Tier 2 (e.g. anode effect frequency and duration) is typically not comparable to data for other technologies (Marks & Nunez 2018b) and could therefore lead to inaccurate results; however, if facility-specific emission factors (e.g. production-based factors to use in Equation 4.25), coefficients or direct measurements (Tier 3_{DM}) are available for $\mathrm{PFPB}_{\mathrm{MW}}$ technology facilities, it is *good practice* to adopt a Tier 3 method.

EQUATION 4.25 (UPDATED)
HVAE PFC EMISSIONS (TIER 1 METHOD)

$$HVAE\ E_{CF_4} = (HVAE\ EF_{CF_4} \bullet MP)$$

and

$$HVAE\ E_{C_2F_6} = (HVAE\ EF_{C_2F_6} \bullet MP)$$

Where:

HVAE E_{CF4} = HVAE emissions of CF_4 from aluminium production, kg CF_4

HVAE E_{C2F6} = HVAE emissions of C_2F_6 from aluminium production, kg C_2F_6

HVAE EF_{CF4} = default HVAE emission factor by cell technology type for CF_4, kg CF_4/tonne Al

HVAE EF_{C2F6} = default HVAE emission factor by cell technology type for C_2F_6, kg C_2F_6/tonne Al

MP = metal production by cell technology type, tonnes Al

Tier 2a and Tier 3a methods for High Voltage Anode Effect (HVAE) emissions: Based on overall anode effect performance and slope coefficient

The Tier 2a and Tier 3a methods estimate HVAE CF_4 emissions based on the relationship between anode effect emissions and total anode effect minutes per cell-day. The slope coefficient is based on direct measurements of PFCs. Tier 2a makes use of average coefficients from measurements at numerous facilities. Tier $3a_{HVAE}$ is based on measurements at the individual facility. Because the process mechanisms that produce PFC emissions during HVAE are similar for CF_4 and C_2F_6, the two gases should be considered together when estimating PFC emissions. C_2F_6 emissions are calculated in the HVAE methods described herein as a fraction of CF_4 emissions.

With an established relationship between anode effect process data and PFC emissions, process data collected on an on-going basis can be used to calculate PFC emissions in lieu of direct measurement of PFCs. Equation 4.26 should be used when anode effect minutes per cell day are recorded. For individual high voltage anode effects, the reported anode effect duration (AED) is the sum of every second where the measured cell voltage is higher than the trigger threshold. The anode effects minutes per cell day (AEM) are calculated based on the sum (in minutes) of all the recorded anode effect minutes divided by the product of the number of cells in the considered section and the respective time in days (US Environmental Protection Agency & International Aluminium Institute 2008).

Because $PFPB_{MW}$ smelters currently do not record shorter-duration anode effects that nevertheless can result in significant PFC emissions, the Tier 2a and $3a_{HVAE}$ methods are not recommended for $PFPB_{MW}$ smelters; however, if these facilities adopt consistent definitions for HVAEs (refer to Box 4.2), then it is possible to use Tier 3a.

Slope Coefficient: The coefficient characterises the kg of CF_4 per tonne of aluminium produced, divided by anode effect minutes per cell-day[6]. Since PFC emissions are measured per tonne of aluminium produced, it includes the effects of cell amperage and current efficiency, the two main factors determining the amount of aluminium produced in the cell. Equation 4.26 describes the method for both CF_4 and C_2F_6.

EQUATION 4.26 (UPDATED)
HVAE PFC EMISSIONS BY SLOPE METHOD (TIER 2A AND TIER 3A METHODS)

$$HVAE\ E_{CF_4} = S_{CF_4} \bullet AEM \bullet MP$$

and

$$HVAE\ E_{C_2F_6} = HVAE\ E_{CF_4} \bullet F_{C_2F_6\ /\ CF_4}$$

Where:

HVAE E_{CF4} = HVAE emissions of CF_4 from aluminium production, kg CF_4

HVAE E_{C2F6} = HVAE emissions of C_2F_6 from aluminium production, kg C_2F_6

S_{CF4} = slope coefficient for CF_4 by cell technology type (Tier 2a) or smelter specific emission ratio (Tier 3a) (kg CF_4/tonne Al)/(AE-Mins/cell-day)

AEM = anode effect minutes per cell-day, AE-Mins/cell-day

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[6] The term ‘cell-day’ refers to the number of cells operating multiplied by the number of days of operation.

MP = metal production, tonnes Al

$F_{C2F6/CF4}$ = weight fraction of HVAE C_2F_6/CF_4, kg C_2F_6/kg CF_4

Tier 3a method for High Voltage Anode Effect (HVAE) emissions: Based on overall anode effect performance and overvoltage coefficient

Overvoltage Coefficient: Some process control systems characterize high voltage anode effects by calculating an Anode Effect Overvoltage[7] (AEO) statistic. AEO is defined as the extra cell voltage above the target operating voltage, and this parameter has been shown to be a good predictor of PFC emissions when recorded by the process control system. The AEO process control technology is in use at a few modern smelters. AEO is calculated by summing the product of time and voltage above the target operating voltage and dividing this figure by the time over which data were collected. As noted above, for years beyond 2019, it is *good practice* to adopt this overvoltage method only at a Tier 3 level; alternatively, if facility-specific overvoltage coefficients are unavailable, it *is good practice* to use the Tier 2a or $3a_{HVAE}$ slope method.

EQUATION 4.27 (UPDATED)
HVAE PFC EMISSIONS BY OVERVOLTAGE METHOD (TIER 3A METHOD)

$$HVAE\ E_{CF_4} = OVC \bullet \frac{AEO}{CE/100} \bullet MP$$

and

$$HVAE\ E_{C_2F_6} = HVAE\ E_{CF_4} \bullet F_{C_2F_6\ /\ CF_4}$$

Where:

$HVAE\ E_{CF4}$ = HVAE emissions of CF_4 from aluminium production, kg CF_4

$HVAE\ E_{C2F6}$ = HVAE emissions of C_2F_6 from aluminium production, kg C_2F_6

OVC = Overvoltage coefficient for CF_4, (kg CF_4/tonne Al)/mV

AEO = anode effect overvoltage, mV

CE = aluminium production process current efficiency expressed, percent (e.g., 95 percent)

MP = metal production, tonnes Al

$F_{C2F6/CF4}$ = weight fraction of C_2F_6/CF_4, kg C_2F_6/kg CF_4

Tier 2b and Tier 3b method for High Voltage Anode Effect (HVAE) emissions: Based on individual anode effect duration

An alternative way to quantify PFC emissions from HVAE for PFPB technology was proposed by (Marks & Nunez 2018a) and by (Dion *et al.* 2018a). This approach considers that the PFC generation rate is not constant throughout the duration of the HVAE but declines as the HVAE continues. Therefore, PFCs are estimated for *each individual* HVAE (based on its duration) and the summation of individual HVAE emissions gives total HVAE emissions.

In general, the Tier 2b method is expected to be more accurate than the Tier 2a method, and the Tier $3b_{HVAE}$ method is similarly expected to be more accurate than the Tier $3a_{HVAE}$ method. The Tier 2b and $3b_{HVAE}$ methods are considered particularly useful for facilities with a low HVAE frequency or when considerable change in the distribution of HVAE duration can be observed (e.g. years when an important relining and start-up of electrolysis cells is expected). Both approaches quantify the PFC emissions from individual HVAEs based on process parameters that are known or calculated by the cell control system.

Tier 2b emission rate coefficients (K_1, K_2 for the Marks & Nunez 2018a method; C_1, C_2, C_3 and C_4 for the Dion *et al.* 2018a method) were calculated based on a set of data collected from different facilities. The Tier 3b methodology uses the same equations as presented below with facility-specific coefficients, based on the results

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[7] Computer control systems report either 'positive' or 'algebraic' overvoltage depending on the version of software used. Use of the expression 'overvoltage' should not be confused with the classical electrochemical terminology, which usually means the extra voltage needed for an electrochemical reaction to occur.

of extensive gas monitoring measurement campaigns. A significant number of individual HVAE, with various durations, should be monitored to obtain accurate coefficients. There is currently no measurement protocol available to determine Tier 3 coefficients based on individual anode effect measurement but there is ongoing work within industry towards publication of an updated protocol.

The Tier 2b and $3b_{HVAE}$ methods require extraction and use of performance data for individual HVAEs to calculate PFC emissions (an alternative would be for cell control systems to automatically calculate and report total emissions from individual HVAEs using the Tier $2b/3b_{HVAE}$ methods). If HVAE performance data is unavailable, an alternative method should be used.

At the Tier 2b level, the choice of method can be based on the following considerations:

1. *Technology Class* – The Marks and Nunez approach is applicable for $PFPB_L$ and $PFPB_M$ technologies; the Dion *et al.* approach is applicable for $PFPB_M$, $PFPB_L$ as well as the SWPB technology class. However, based on the lowest uncertainties for each technology (refer to Table 4.16b), the Marks and Nunez method is recommended for $PFPB_L$ technology, whereas the Dion *et al.* approach is recommended for the $PFPB_M$ and SWPB technology classes. For all other technology classes, it is *good practice* to employ facility-specific Tier 3b coefficients or alternative methods.
2. *Distribution of individual HVAE durations (AED) at the facility* – The Dion *et al.* approach is limited to AEDs up to 1000 s for estimating CF_4 and 150 s for C_2F_6, whereas the Marks & Nunez approach has the advantage of no limitations on AED. Therefore, if a facility has a substantial proportion of HVAEs (e.g. more than 5 percent) with AED greater than 150s, it is *good practice* to use the Marks and Nunez method or alternative methods.

Marks & Nunez approach: The approach proposed by (Marks & Nunez 2018a) uses different coefficients depending on individual AED, as presented in Equation 4.27a. Note that for the Tier 2b approach, Tier 2b emission rate coefficients (K_1 and K_2) are presented in Table 4.16a; these coefficients apply only to $PFPB_M$ and $PFPB_L$ technologies. For Tier 2, weight fractions of C_2F_6/CF_4 by technology class are given in Table 4.16 (these are the same weight fractions as for the Tier 2a method).

EQUATION 4.27A (NEW)
HVAE PFC EMISSIONS (TIER 2B AND TIER 3B METHOD – (MARKS & NUNEZ 2018A))

$$HVAE\ E_{CF_4} = \sum [(K_1 \bullet AED_i^{K_2}) \bullet \frac{kA_i}{1000}]$$

and

$$HVAE\ E_{C_2F_6} = HVAE\ E_{CF_4} \bullet F_{C_2F_6\ /\ CF_4}$$

Where:

$HVAE\ E_{CF4}$ = Total HVAE CF_4 produced during the considered period, as the sum of all individual 'i' HVAE emissions, kg CF_4

$HVAE\ E_{C2F6}$ = HVAE emissions of C_2F_6 from aluminium production, kg C_2F_6

AED_i = Total duration of each individual 'i' HVAE, during which the cell voltage is above the HVAE detection threshold, s

kA_i = Average potline current during each individual 'i' HVAE, kA

K_1 = Emission rate coefficient dependant on the AED, dimensionless

K_2 = Emission rate coefficient dependant on the AED, dimensionless

$F_{C2F6/CF4}$ = weight fraction of HVAE C_2F_6/CF_4, kg C_2F_6/kg CF_4

Dion *et al.* approach: The approach proposed by (Dion *et al.* 2018a) to quantify total CF_4 and C_2F_6, from the sum of emissions from individual HVAEs is presented in Equation 4.27b. Tier 2b emission rate coefficients (C_1,C_2,C_3 and C_4) are calculated using Equation 4.27f. Note that use of the Tier 2b emission rate coefficients are only for (i) $PFPB_M$ and $PFPB_L$ and SWPB technology classes and (ii) HVAEs with durations (AED) *below* 1000 s for CF_4 estimation and *below* 150 s for C_2F_6 estimation, based on the data set used by (Dion *et al.* 2018a). For other technologies or longer duration HVAEs, it is *good practice* to employ Tier 3b coefficients or an alternative method.

EQUATION 4.27B (NEW)
HVAE PFC EMISSIONS (TIER 2B AND TIER 3B METHOD – (DION *ET AL.* 2018A))

$$HVAE\ E_{CF_4} = \sum [(C_1 \bullet AED_i^{C_2}) \bullet MP_{Day}] / 1000$$

and

$$HVAE\ E_{C_2F_6} = \sum [(C_3 \bullet AED_i^{C_4}) \bullet MP_{Day}] / 1000$$

Where:

HVAE E_{CF4} = Total HVAE CF_4 produced during the considered period, as the sum of all individual HVAE emission, kg CF_4

HVAE E_{C2F6} = Total HVAE C_2F_6 produced during the considered period, as the sum of all individual HVAE emission, kg C_2F_6

AED_i = Total duration of each individual '*i*' HVAE during which the cell voltage is above the HVAE detection threshold, s

MP_{Day} = Average daily metal production per cell[8], tonnes Al

C_1 = Emission rate coefficient for CF_4 dependant on the metal production of the cell, g CF_4 /s-tonne Al

C_2 = Emission rate coefficient for CF_4 dependant on the metal production of the cell, dimensionless.

C_3 = Emission rate coefficient for C_2F_6 dependant on the metal production of the cell, g C_2F_6/s-tonne Al

C_4 = Emission rate coefficient for C_2F_6 dependant on the metal production of the cell, dimensionless.

ESTIMATING EMISSIONS FROM LOW VOLTAGE ANODE EFFECTS[9]

Tier 1 method for Low Voltage Anode Effect (LVAE) emissions

The Tier 1_{LVAE} method uses technology-based default emission factors for the main production technology types ($PFPB_L$, $PFPB_M$, SWPB, VSS and HSS). PFC emissions can be estimated according to Equation 4.27c. There is no Tier 1_{LVAE} default emissions factor for $PFPB_{MW}$ as an estimate for LVAE emissions is already included in the Tier 1_{HVAE} default emissions factor as this value was derived from *total* PFC measurement data. The level of uncertainty in the Tier 1 method is much greater than the level of uncertainty in the Tier 3 methods because individual facility operating characteristics are not taken into account. Tier 1 is consistent with *good practice* when PFCs from primary aluminium is not a *key category* or when smelter specific LVAE emissions data are not available from operating facilities.

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[8] MP_{Day} in Equation 4.27b is the average metal production *per cell per day* – it can be estimated from potline data or from the line amperage and average current efficiency of the potline. Care should be taken not to confuse this with the variable '*MP*' – total metal production from the facility over the accounting period – used in other equations.

[9] C_2F_6 emissions were not considered in the estimation of LVAE as C_2F_6 concentrations from LVAE are most of the time undetectable. The level of these emissions is in the low ppb and within the noise level of the measuring instrument. Some research (Asheim *et al.* 2014; Dion *et al.* 2016) has even concluded that formation of C_2F_6 from LVAE does not occur, or occurs at level so low, it is considered negligible.

EQUATION 4.27C (NEW)
LVAE PFC EMISSIONS (TIER 1 AND TIER 3 METHODS – PRODUCTION-BASED)

$$LVAE\ E_{CF_4} = (LVAE\ EF_{CF_4} \bullet MP)$$

Where:

$LVAE\ E_{CF4}$ = LVAE emissions of CF_4 from aluminium production, kg CF_4

$LVAE\ EF_{CF4}$ = LVAE emission factor for CF_4 (Tier 1 default by cell technology type, or Tier 3 facility-specific), kg CF_4/tonne Al

MP = metal production by cell technology type, tonnes Al.

Tier 3 methods for Low Voltage Anode Effect (LVAE) emissions

The Tier 3 methods for estimating LVAE emissions multiply facility-specific factors either by (i) metal production (Equation 4.27c) or (ii) as a ratio of HVAE emissions (Equation 4.27d). The method based on metal production is analogous to the Tier 1 method for LVAE. The method based on ratio of HVAE emissions assumes that HVAE emissions reflect the overall performance and process control of the smelter. For both methods, it is *good practice* to define the facility-specific emission factor (LVAE EF_{CF4}), or emission ratio of LVAE to HVAE emissions ($ER_{LV\ CF4}$) based on direct PFC measurements at the facility. Preliminary testing of both methods produced results that were broadly aligned and consistent with the direct measurements of PFCs (Marks & Nunez 2018b).

A Tier 2 method for LVAE emissions has not been provided, since use of $ER_{LV\ CF4}$ emission ratios for different technology classes would *not* reduce uncertainty levels compared to a Tier 1 approach. This is because a Tier 2 $ER_{LV\ CF4}$ emission ratio approach cannot capture all the underlying factors that drive LVAE emissions in one smelter versus another of the same technology class. Therefore, this method is only recommended at a Tier 3 individual facility level.

EQUATION 4.27D (NEW)
LVAE PFC EMISSIONS (TIER 3 METHOD – AS RATIO OF HVAE EMISSIONS)

$$LVAE\ E_{CF_4} = HVAE\ E_{CF_4} \bullet ER_{LV\ CF_4}$$

Where:

$LVAE\ E_{CF4}$ = low voltage anode effect emissions of CF_4 from aluminium production, kg CF_4

$HVAE\ E_{CF4}$ = high voltage anode effect emissions of CF_4 from aluminium production by cell technology, kg CF_4

$ER_{LV\ CF4}$ = Smelter-specific ratio of LVAE/HVAE CF_4 emissions

ESTIMATING EMISSIONS FROM CELL START-UP

Tier 2 and 3 methods for Cell Start-Up (CSU) emissions

For completeness, it is *good practice* to always include CSU emissions (refer to Box 4.3) in total PFC emissions estimates. There are various ways CSU emissions can be included depending on the methodological Tier selected. The Tier 1 HVAE and LVAE default emission factors implicitly include CSU emissions; therefore, where the Tier 1 methods are used, there is no need to estimate CSU emissions separately. The Tier 2a and 2b HVAE methods and the Tier 3a and $3b_{HVAE}$ methods can account for CSU emissions if data on anode effect duration and frequency are collected during CSUs and are included in the emissions calculations. As discussed below, this may lead to a slight overestimate of emissions if the Tier 2a or 3a slope factor method is used. Finally, the Tier 3_{DM} direct measurement method includes CSU emissions as long as the continuous emissions monitoring occurs during CSU periods.

BOX 4.3 (NEW)
PFC EMISSIONS DURING START-UP OF ELECTROLYSIS CELLS

New electrolysis cells undergo a 'start-up' process prior to normal operation. The 'start-up' period can vary from one facility to another, e.g. from the first few hours of a cell's life to a month.

HVAEs can occur during start-ups of electrolysis cells – from the moment when the anode beam is first raised on the cell and metal starts being produced – leading to generation of PFC emissions (International Aluminium Institute 2006; Dando *et al.* 2008; Xu *et al.* 2008; Dando *et al.* 2009; Maltais *et al.* 2010). While some researchers (Kristensen *et al.* 2007; Reny *et al.* 2016) have shown that cell start-ups can be done without HVAE, it is not common practice and PFC emissions from cell start-ups may contribute to a significant proportion of a facility's total PFC emissions during certain periods, especially when the aluminium smelter is annually carrying out a large number of cell start-ups.

While some facilities have historically included the start-up period in accounting HVAE emissions, others have excluded it given that it does not represent normal operations. It is thought that LVAE emissions may also occur during the start-up period.

Furthermore, new cells following start-up typically operate with a higher cell voltage than during normal operation. For this reason, some smelters use a different HVAE detection threshold (e.g. 9.5 volts instead of 8 volts) for a specific period to reduce the risk of falsely detecting HVAE (Dando et al. 2008). This detection threshold is specific to each facility (based on historical data) and should be used for calculating HVAE performance at the facility when estimating cell start-up emissions using any of the methods described here.

HVAE PFC emissions measured during CSU events have demonstrated lower emission rates than during normal operations. For this reason, accounting for these HVAEs using the standard slope or overvoltage coefficient during normal operations for the technology class (Tier 2a) or facility (Tier 3a) may lead to an overestimation of these PFC emissions (Dando *et al.* 2008; Xu *et al.* 2008; Maltais *et al.* 2010).

To avoid overestimating emissions from CSUs through use of the Tier 2a or $3a_{HVAE}$ methods, inventory compilers have three options. Lowest uncertainties will be obtained with the second and third options presented below as they are based on specific measurements during CSU. However, as a significant amount of CSU measurements may prove difficult to acquire, it is *good practice* to consider the first option when no facility-specific data for cell start-up is available. As a first option to take into consideration the different process dynamics of HVAEs during the start-up of cells, compilers can use the Tier 2b or $3b_{HVAE}$ non-linear approach (Equations 4.27a or 4.27b) when no facility-specific measurement data for cell start-up is available. LVAE emissions during cell-start-up can then be estimated using either a production-based Tier 1 or Tier 3 approach (Equation 4.27c), or Tier 3 ratio of HVAE emissions approach (Equation 4.27d).

As a second option, inventory compilers using the Tier 3a method can avoid overestimates by developing and applying slope or overvoltage coefficients specifically for CSUs at the facility (in addition to the coefficients for normal operation). Again, LVAE during start-up emissions may be estimated using a Tier 1 or Tier 3 approach.

The third alternative, when data is available, compilers may determine a facility-specific Tier 3 emission factor based on the total emissions of PFC per cell start-up at the facility. This Tier 3_{CSU} method accounts for both HVAE and LVAE emissions during the start-up process, as given in Equation 4.27e:

EQUATION 4.27E (NEW)
TOTAL PFC EMISSIONS FOR START-UP OF ELECTROLYSIS CELLS (TIER 3_{CSU} METHOD)

$$CSU\ E_{CF_4} = (EF_{CSU\,CF_4} \bullet N_{CSU})$$

And

$$CSU\ E_{C_2F_6} = (EF_{CSU\,C_2F_6} \bullet N_{CSU})$$

Where:

E_{CF4} = Total amount of CF_4 produced during start-ups for a specific period, kg CF_4

E_{C2F6} = Total amount of C_2F_6 produced during start-ups for a specific period, kg C_2F_6

EF_{CSU_CF4} = Average amount of CF_4 produced during the cell start-up period, kg CF_4 / cell start-up

EF_{CSU_C2F6} = Average amount of C_2F_6 produced during the cell start-up period, kg C_2F_6 / cell start-up

N_{CSU} = Total number of cell start-ups during the specific period considered, cell start-up

Note that Equation 4.27e should be used to estimate CSU emissions *only if* CSU emissions are excluded from normal HVAE and LVAE accounting. Care should be taken not to double count CSU emissions if they are already included in the normal accounting of HVAE and LVAE emissions.

DIRECT MEASUREMENT OF TOTAL EMISSIONS

Tier 3_{DM} method for Total PFC emissions: Based on direct gas measurement

The Tier 3_{DM} method is based on direct measurement of *total* PFC gases (CF_4 and C_2F_6) at individual facilities, rather than estimating emissions through emission factors or coefficients and process data (e.g. anode effect minutes per cell-day). As total emissions are measured, there is no need to account for PFCs from high and low voltage anode effects (HVAE and LVAE) separately. Furthermore, cell start-up (CSU) emissions are included since direct measurements should provide representative coverage of emissions from all operations. The Tier 3_{DM} method, following industry best practices, provides the lowest of uncertainty level for all accounting methods, since the only sources of uncertainty is related to sampling procedures and measurement error.

Measurement approaches are only briefly described here. For detailed guidance on direct measurement of PFCs, refer to established standard measurement practices and the latest industry protocols (e.g. (US Environmental Protection Agency & International Aluminium Institute 2008)). The inventory compiler should also consult guidance on plant-level measurements outlined in Volume 1, Chapter 2, and on QA/QC of measurements in Volume 1, Chapter 6. Two approaches for direct PFC measurements are (i) *time-integrated* measurements and (ii) *continuous* measurements. While neither are routinely carried out by the industry at present, both have the potential to provide continuous coverage of total emissions.

Time-integrated measurements are periodic measurements where PFCs from the facility are collected in sampling containers over set time-intervals; gas samples are then analysed ‘off-line’ in a laboratory. Examples of analysis techniques include: Gas Chromatography with Mass Spectrometry (GC/MS) and Fourier Transform Infrared Spectrometry (FTIR). Time-integrated measurements are typically simpler and more cost-effective to operate and often provide more accurate (with lower limits of detection) than *continuous* measurement approaches (US Environmental Protection Agency & International Aluminium Institute 2008; Fraser *et al.* 2013). For time-integrated measurements, it is *good practice* to provide continuous coverage over time as this ensures measurements are representative of all smelter operations. For more details, refer to the latest industry measurement protocol for PFC measurements.

Continuous measurements are those where PFCs are measured continuously by *in-situ* instruments at the facility. These have advantages of: (i) providing continuous coverage of total emissions and (ii) allowing emissions from high vs. low voltage anode effects (HVAE and LVAE) to be accounted for separately (US Environmental Protection Agency & International Aluminium Institute 2008). However, this approach can be more cost-intensive and may require specialist expertise to operate and maintain. Examples of measurement techniques include: FTIR, Mass Spectrometry (MS), Photoacoustic Spectrometry (PAS), Tunable-Diode Laser Absorption Spectrometry (TDLAS) and Quantum-Cascade Lasers (QCL) (Aarhaug *et al.* 2018). For accurate capture of LVAE emission components, an important consideration is the detection limit of measuring instrumentation, given that LVAE emissions are typically at low concentrations (as low as ppb levels); this introduces a further level of uncertainty for continuous measurement approaches.

To ensure the accuracy of emissions accounting by direct measurement, it is *good practice* to employ established measurement practices and the latest industry protocols (US Environmental Protection Agency & International Aluminium Institute 2008). There is ongoing work to develop an updated measurement protocol for total PFC emissions (particularly LVAE emissions) to improve consistency and alignment across the industry.

4.4.2.4 CHOICE OF EMISSION FACTORS FOR PFCS

Tier 1: Technology based default emission factors

Default emission factors for the Tier 1 method are provided in Table 4.15. These are for estimation of both HVAE emissions (Equation 4.25) and LVAE emissions (Equation 4.27c). Aluminium production data by technology is usually available through national statistics publications or through publicly available company reports and websites.

Note that for the PFPB$_{MW}$ technology class, the HVAE-CF$_4$ emission factor in Table 4.15 includes LVAE emissions and therefore represents total CF$_4$ emissions.

TABLE 4.15 (UPDATED)
TECHNOLOGY SPECIFIC DEFAULT EMISSION FACTORS FOR THE CALCULATION OF HVAE AND LVAE EMISSIONS FROM ALUMINIUM PRODUCTION (TIER 1 METHOD) (MARKS & NUNEZ 2018B)

Technology	HVAE				LVAE	
	CF$_4$		C$_2$F$_6$		CF$_4$	
	EF$_{CF4}$ (kg/tonne Al)	Uncertainty Range (%)[b]	EF$_{C2F6}$ (kg/tonne Al)	Uncertainty Range (%)	EF$_{CF4}$ (kg/tonne Al)	Uncertainty Range (%)
PFPB$_L$	0.016[a]	-82/+126[a]	0.001	-74/+109[a]	0.009[a]	+99/-61
PFPB$_M$	0.011	-90/+213	0.001	-90/+256	0.018	+247/-98
PFPB$_{MW}$	0.161[b]	-85/+476	0.013[b]	-98/+864	-	-
SWPB	0.354	-76/+116	0.093	-89/+68	0.010	+69/-69
VSS	0.159[c]	-94/+580[c]	0.009[c]	-94/+525	0.001	+61/-52
HSS	0.477	-79/+112	0.033	-76/+86	0.026	-[d]

Notes:

[a] PFPB$_L$ emission factors and uncertainties reported in (Marks & Nunez 2018b) erroneously included data from another technology class (PFPB$_M$). This has since been corrected in the emission factor and uncertainty values reported here (expert opinion – Dr Jerry Marks).

[b] PFPB$_{MW}$ emission factor (EF) is based on total emissions measurement data which includes LVAE emissions.

[c] VSS emission factors (EF) and uncertainties here incorporate data sets from (Marks & Nunez 2018b) and (Burkat, V.S. et al. 2018)

d Single data point – no uncertainty range calculated.

Tier 2a: HVAE-PFC emission factor based on technology specific relationship between overall anode effect performance and PFC emissions

The Tier 2a slope method (Equation 4.26) is based on using technology specific coefficients for the applicable reduction cell and process control technology as listed in Table 4.16.

TABLE 4.16 (UPDATED)
TECHNOLOGY SPECIFIC COEFFICIENTS FOR THE CALCULATION OF HVAE PFC EMISSIONS FROM ALUMINIUM PRODUCTION USING SLOPE[10] METHODOLOGY (TIER 2A METHOD) (MARKS & NUNEZ 2018B)

Technology	CF_4		Weight Fraction C_2F_6/CF_4	
	SC_{CF4} (kg CF_4/tonne Al)/(AE-Mins/cell-day) a	**Uncertainty Range (%)**	**C_2F_6/CF_4**	**Uncertainty range (%)**
$PFPB_L$	0.122	-48/+45	0.097	-35/+31
$PFPB_M$	0.104	-27/+32	0.057	-55/+55
$PFPB_{MW}$[a]	-	-	-	-
SWPB	0.233	-27/+44	0.280	-55+58
VSS	0.058	-53/+130	0.086	-76/+236
HSS	0.165	-47/+28	0.077	-61/+48

Note:

[a] Tier 2 default coefficients are not available for $PFPB_{MW}$ technology class (Modern PFPB without fully automated anode effect intervention strategies for PFC emissions) because process data for anode effect frequency and duration was either not available, or, not comparable to traditional definitions or thresholds associated with anode effects.

Tier 2b: HVAE-PFC emission rate coefficients based on individual anode effect durations

Marks & Nunez approach: The Tier 2b method proposed by (Marks & Nunez 2018a) (Equation 4.27a) uses different emission rate coefficients to estimate HVAE-CF_4 emissions, based on the anode effect duration (AED) of individual high voltage anode effects, as listed below in Table 4.16a.

For estimation of HVAE-C_2F_6 emissions, the Tier 2a technology-specific weight fractions of C_2F_6/CF_4 ($F_{C2F6/CF4}$) should be used – refer to Table 4.16.

TABLE 4.16A (NEW)
SPECIFIC HVAE-CF_4 EMISSION RATE COEFFICIENTS BASED ON THE ANODE EFFECT DURATION AS CALCULATED BY (MARKS & NUNEZ 2018A) (TIER 2B METHOD).

AED[a]	Value of K_1	Value of K_2
1s < AED ≤5s	0.0341	0.756
5s > AED≤200s	0.0473	0.693
AED >200 s	0.1661	0.479

[a] In the rare occurrences where AED is equivalent to 0s, the equation that should be used is: kg $CF_4 = 0.576 \cdot kA /1000$

Dion *et al.* approach: For the Tier 2b method proposed by (Dion *et al.* 2018a) to calculate HVAE emissions (Equation 4.27b), emission rate coefficients C_1, C_2, C_3 and C_4 are defined in Equation 4.27f below for the generic smelter, based on the daily metal production per cell.

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[10] The ‘Overvoltage method’ (Equation 4.27) is no longer widely adopted within the aluminium industry. Therefore, there is insufficient data available to update the overvoltage coefficients related to the overvoltage methodology. It is *good practice* to compile PFC inventories using the slope model for recent and future calculations. Tier 3 overvoltage coefficients can still be used as they are facility-specific (Dion et al. 2017; Marks & Bayliss 2012).

EQUATION 4.27F (NEW)
EMISSION RATE COEFFICIENTS FOR HVAE PFC (TIER 2B METHOD – (DION *ET AL.* 2018A))

$$C_1 = 0.6415 \bullet MP_{Day} + 5.878$$

$$C_2 = -0.0972 \bullet MP_{Day} + 0.8905$$

$$C_3 = 0.238 MP_{Day}^2 - 1.407 \bullet MP_{Day} + 2.342$$

$$C_4 = -0.0981 MP_{Day}^2 + 0.381 \bullet MP_{Day} + 0.3413$$

Where :

C_1 = Emission rate coefficient for CF_4 dependant on the metal production of the cell, g CF_4 / s · tonne Al

C_2 = Emission rate coefficient for CF_4 dependant on the metal production of the cell, dimensionless

C_3 = Emission rate coefficient for C_2F_6 dependant on metal production of the cell, g C_2F_6 / s · tonne Al

C_4 = Emission rate coefficient for C_2F_6 dependant on the metal production of the cell, dimensionless.

MP_{Day} = Average daily metal production per cell[11], for the cell technology, tonnes Al

Uncertainty levels when calculating PFCs from individual HVAE: The uncertainty range of each Tier 2b methodology was estimated for SWPB, $PFPB_M$ and $PFPB_L$ technologies in order to facilitate the choice of one of the two methods. These are shown in Table 4.16b.

TABLE 4.16B (NEW)
UNCERTAINTY RANGE[C] (%) IN ESTIMATING PFC EMISSIONS FROM INDIVIDUAL HVAES (TIER 2B METHODS)

Technology	CF_4 [a,b]		C_2F_6 [a,b]	
	Marks & Nunez approach	**Dion *et al.* approach**	**Marks & Nunez approach**	**Dion *et al.* approach**
SWPB	-	-36 / +51	-	-42 / +68
$PFPB_L$	-47 / +29	-36 / +51	-52 / +39	-42 / +68
$PFPB_M$	-16 / +134	-33 / +61	-54 / +152	-24 / +13

Note:

[a] Uncertainty ranges were evaluated for total emissions across multiple measurement campaigns and facilities (expert opinion). Overall, 11 measurement campaigns for $PFPB_M$ and 10 measurements campaigns with $PFPB_L$ or SWPB technology classes were used to estimate the uncertainties related to CF_4, while 5 measurement campaigns for $PFPB_M$ and 4 measurements campaigns with $PFPB_L$ or SWPB technology classes were used to estimate the uncertainties related to C_2F_6 .

[b] Uncertainty ranges were calculated for HVAE emissions, where HVAEs were within the recommended HVAE duration (AED) limits of the (Dion *et al.* 2018a) method. It is possible that the uncertainty increases if the AED exceeds recommended limits when using the (Dion *et al.* 2018a) method, i.e. 1000 s and 150 s for CF_4 and C_2F_6 estimations, respectively.

[c] The uncertainty range calculated in Table 4.16B is based on a comparison with direct measurements and should not be compared to the reported Tier 2a uncertainty range from table 4.16 which compares variations of EF. For comparison, the calculated CF_4 uncertainty range for Tier 2a based on direct measurements is (-44% / + 388%) for legacy facilities and (-22% / + 256%) for modern facilities. The calculated C_2F_6 uncertainty range for Tier 2a based on direct measurements is (-58% / + 8%) for legacy facilities and (-19% / +97 %) for modern facilities.

Tier 3: PFC emission factors based on a facility specific relationship between HVAE and LVAE performance and PFC emissions

Tier 3 methods are based on facility-specific coefficients or emission factors to estimate PFCs:

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[11] MP_{Day} in Equation 4.27g is the average metal production *per cell per day* – it can be estimated from potline data or from the line amperage and average current efficiency of the potline. Care should be taken not to confuse this with the variable '*MP*' – total metal production from the facility over the accounting period – used in other equations.

For HVAE emissions, Tier $3a_{HVAE}$ and $3b_{HVAE}$ coefficients characterize the relationship between facility HVAE performance and measured PFC emissions from periodic or continuous measurements that are consistent with established measurement practices and latest industry protocols (US Environmental Protection Agency & International Aluminium Institute 2008).

For LVAE emissions, facility-specific Tier 3_{LVAE} LVAE/HVAE emission ratios or LVAE emission factors can be established based on direct measurement of HVAE and LVAE for a period of time. There is ongoing work to develop an updated measurement protocol for LVAE emissions to improve consistency and alignment across the industry.

For cell start-up (CSU) emissions, Tier 3_{CSU} production-based emission factors can be established based on direct measurement of HVAE and LVAE emissions during the start-up of electrolysis cells; alternatively, direct measurements can also be used to define Tier $3a_{HVAE}$ or $3b_{HVAE}$ and 3_{LVAE} coefficients for emissions estimation (described above) specifically for cell start-up periods.

Tier 3_{DM} is based on direct measurement at facilities, rather than estimation using on emission factors or coefficients.

4.4.2.5 CHOICE OF ACTIVITY DATA

Production statistics should be available from every facility to enable use of Tier 1 methods for both CO_2 and PFC emissions. Uncertainty in the tonnages of aluminium produced is likely to be low in most countries. Given the expected universal availability of production data, production capacity data should only be used as a check on production statistics.

For CO_2 emissions, all aluminium smelters collect data to support Tier 2 or Tier 3 methods. Søderberg smelters collect anode paste consumption data while Prebake smelters record baked anode consumption. The Tier 2 and Tier 3 methods use the same equation for calculation of CO_2 emissions; however, the Tier 3 method uses facility specific composition data for anode materials while the Tier 2 method uses industry average anode composition data.

Good practice methods for PFC emissions resulting from high voltage anode effects (HVAE) require accurate HVAE minutes per cell day data for all cell types. Annual statistics should be based on the production-weighted average of monthly HVAE effect data. The Tier $2a_{HVAE}$ and Tier $3a_{HVAE}$ slope method utilizes *overall* performance statistics for HVAE minutes per cell day and aluminium production data and Tier $3a_{HVAE}$ overvoltage method utilizes overall performance statistics for anode effect overvoltage and current efficiency. Similarly, Tier $2b_{HVAE}$ and Tier $3b_{HVAE}$ utilises data on *individual* HVAE performance (anode effect duration) and line amperage or daily average metal production at each facility.

Good practice methods for PFC emissions resulting from low voltage anode effects (LVAEs) require accurate aluminium production data for Tier 1 (based on production-based, default emission factors) and Tier 3 (based on production-based, facility-specific emission factors). For the alternative Tier 3 estimation based on the ratio of LVAE/HVAE emissions, *good practice* methods for HVAE should be adopted as these are used in the calculation of LVAE emissions.

Good practice methods for PFC emissions from cell start-up (CSU) requires the same activity data described above for HVAE and LVAE emissions (if using Tiers 2a, 2b, $3a_{HVAE}$ or $3b_{HVAE}$ and Tiers 1_{LVAE} or 3_{LVAE}), however with a data set specific to cell start-ups. Alternatively, if using Tier 3_{CSU} facility-specific emission factors defined for cell start-ups, the only activity data required is the number of cell start-ups over the accounting period.

The direct measurement method for total PFCs (Tier 3_{DM}) is not based on estimation and no activity data is required.

Individual aluminium companies or industry groups, national aluminium associations or the International Aluminium Institute (IAI) should be consulted to ensure that the data are available and in a useable format for inventory estimation.

4.4.2.6 COMPLETENESS

Completeness for the aluminium production source category requires reporting of emissions of all GHGs (CO_2, CF_4, and C_2F_6) from all sources (see Table 4.14) for all aluminium production in all smelters in a country. Primary aluminium facilities will generally have good records of tonnes of aluminium produced throughout the entire time series covered by the inventory. In addition, carbon consumption data are typically available over the same period. Process data on high voltage anode effects may be incomplete over the entire time series and measures may have to be employed, such as those described in Section 4.4.2.7, Developing a Consistent Time Series, to calculate PFC emissions over some portions of the inventory period. Primary aluminium production also utilizes large amount of electricity and care should be exercised to avoid omissions of carbon dioxide associated with electricity input, or, to avoid double counting of this carbon dioxide.

Furthermore, updates here in the *2019 Refinement* provide significant advances in completeness, given the inclusion of accounting for: (i) PFC emissions from LVAEs from primary aluminium production and (ii) PFC emissions from cell start-ups (CSU), both of which were not previously accounted for in the *2006 IPCC Guidelines*. Despite greater completeness compared to the *2006 IPCC Guidelines*, a higher level of uncertainty (imprecision) overall is introduced in estimating total PFCs, given the higher uncertainties in accounting LVAE emissions. Finally, care should be exercised to avoid double counting of PFCs from cell start-ups, if these are already accounted for in normal HVAE and LVAE emissions.

4.4.2.7 DEVELOPING A CONSISTENT TIME SERIES

General guidance on managing time-series consistency is available in Volume 1, Chapter 5; however, the following provides guidance specific to aluminium production.

Time-series consistency for CO_2 emissions

Aluminium production statistics will typically be available for the entire history of the facility. Developing a consistent time series for carbon dioxide emissions should not be a problem since most facilities historically have measured and recorded anode or paste consumption. Where historic anode or paste consumption data are missing, carbon dioxide emissions can be estimated from aluminium production utilizing the Tier 1 method.

Time-series consistency for High Voltage Anode Effect (HVAE) PFC emissions

A complete time series of PFC related activity data such as high voltage anode effect (HVAE) minutes per cell day or overvoltage gives the best time series results. Because PFC emissions only became a major focus area in the early 1990s for the global aluminium industry, some facilities may have limited information about the required anode effect data to implement Tier 2 or Tier 3 PFC inventory practices over the entire time covered by the inventory. Substantial errors and discontinuities can be introduced by reverting to Tier 1 methods for PFC emissions for years for which activity data are not available. The appropriateness of applying Tier 2 or Tier 3 PFC emission factors back in time to a given facility and availability of detailed process data vary with the specific conditions. Generally, backcasting of Tier 2 or Tier 3 methods using splicing or surrogate data are preferred over use of Tier 1 emission factors. Specifically, where only HVAE frequency data are available and HVAE duration data are unavailable, it is *good practice* to splice or backcast PFC emissions per tonne aluminium based on HVAE frequency data (implicitly assuming that anode effect durations did not change).

When going back in time using the Tier 1 or Tier 2a methodologies, it is important to take into consideration the change in emission factors (for Tier 1) and slope coefficients for HVAEs (for Tier 2a). Accordingly, when using these methods, it is generally *good practice* to use the default Tier 1 EFs and default Tier 2a slope coefficients in the *2006 IPCC Guidelines* prior to 2006. From 2006 through to the median year listed for each cell technology in Table 4.16c, default Tier 1 EFs and default Tier 2a slope coefficients can be interpolated from the *2006 IPCC Guidelines* and the *2019 Refinement*. After that median year, the default Tier 1 EFs and default Tier 2a slope coefficients from the *2019 Refinement* should be used. As noted in section 4.4.1, the technology class in the *2006 IPCC Guidelines* that corresponds to the $PFPB_L$ and $PFPB_M$ technology classes is CWPB. Because there is no technology class in the *2006 IPCC Guidelines* that corresponds well to the $PFPB_{MW}$ class, inventory compilers should use the default EF for $PFPB_{MW}$ from the *2019 Refinement* for the entire time series (i.e. from the time the $PFPB_{MW}$ technology was first introduced into the country).

Inventory compilers switching from the Tier $3a_{HVAE}$ overvoltage methodology to the Tier $3a_{HVAE}$ slope model should use both methods in parallel for a period of three years to evaluate the potential impact. However, publications demonstrated that the difference between both methods should be negligible with Tier 3 emission factors (Dion et al. 2017; Marks & Bayliss 2012). If the difference between both methods is greater than 5 percent over the transition period, then *good practices* would require contacting the International Aluminum Institute (IAI) to be directed to expert advice to determine the optimal course of action for the best representativeness.

For inventory compilers switching from Tier 2a-$3a_{HVAE}$ (slope/overvoltage) to the Tier 2b-$3b_{HVAE}$ (non-linear) methodology to estimate HVAE emissions, it is consistent with *good practices* to adopt a similar protocol, i.e. evaluate both methods in parallel for three years to evaluate impacts and if greater than 5 percent differences are noted during the transition period, the IAI can be contacted for expert advice. Backcasting PFC emissions using Tier 2b in 2019 and prior years is also possible, provided historical data on individual HVAE durations is still available.

Currently many facilities are making PFC measurements that facilitate implementation of Tier 3 PFC inventory methods. There are a number of issues that impact on whether Tier 3 PFC emission factors can be extrapolated to past inventory periods. Factors that should be considered include: (i) whether any technology upgrades have been implemented at the facility, including significant amperage increase, new cell control system, or significant changes in alumina feed control strategy affecting the frequency of HVAEs, (ii) whether there have been substantial changes in work practices affecting the distribution of the HVAE durations, (iii)_whether any changes in the calculation of underlying process data have occurred, and (iv) the quality of the measurements made to establish the Tier 3 factor or coefficient. It is *good practice* to consult with representatives from the operating facilities, either directly or through regional or international organizations representing the industry to develop the best strategy for the specific group of operating locations included in the national inventory. Additional information on splicing methods and details regarding constructing a time series for primary aluminium is available in The Aluminium Sector GHG Protocol (International Aluminium Institute 2006). Expert advice is also available from global and regional aluminium industry associations regarding greenhouse gas emissions and typical industry emissions from aluminium production.

Table 4.16c has been provided to facilitate the choice of the correct HVAE emission factor (EF) for time consistent inventories.

TABLE 4.16C (NEW)
TIME PERIOD OF MEASUREMENTS USED TO ESTABLISH UPDATED TIER 1 DEFAULT EFS AND TIER 2A DEFAULT SLOPE COEFFICIENTS

Technology	Time Period	Use 2006 Guideline Defaults till 2006, then interpolate through to (Median Year)[1]
$PFPB_L$	2013-2014	2013
$PFPB_M$	2013-2016	2013
$PFPB_{MW}$	2008-2012	Use *2019 Refinement* Tier 1 EF for entire time series[2]
SWPB	2004-2015	2008
VSS	2003-2016	2007
HSS	2004-2012	2007

[1] For each cell technology, the transition point is dependent on the time period when facility measurements were obtained. Here the median year for measurements is recommended as the transition point to use updated default EFs and coefficients from the *2019 Refinement.*

[2] For $PFPB_{MW}$ technology, median year is 2011, however use of updated Tier 1 EF is recommended for the entire time series.

Time-series consistency for Low Voltage Anode Effect (LVAE) PFC emissions

Low voltage anode effects (LVAEs) became a concern for the aluminium industry in the early 2010s, due to an increase number of cell technologies with higher amperage and additional anodes (Chen *et al.* 2013; Wong & Marks 2013; Zarouni *et al.* 2013; Dando *et al.* 2015; Wong *et al.* 2015; International Aluminium Institute 2018). Actual data indicates that these PFC emissions are greater for specific cell technologies, usually with cell amperage higher than 350kA. Therefore, inventory compilers should backcast the LVAE PFC emissions, for national inventories, by using the respective Tier 1 coefficient specific to each category back to 2006. Since 2006, the global aluminium industry has undergone changes in technology and operating conditions that make LVAE emissions much more prevalent[12]; these changes have occurred not only through uptake of newer technologies (e.g. $PFPB_L$ to $PFPB_M$) but also during upgrades *within* the same technology in order to maximise productivity and reduce energy use (Coursol *et al.* 2011, Kalban *et al.* 2013, Tarcy *et al.* 2011). The relative insignificance of emissions from LVAE before 2006 is also supported by (i) the lack of industry reports detecting LVAE emissions in PFC measurements prior to 2006, (ii) the very high frequencies of HVAEs (and hence high HVAE emissions) prior to 2006 outweighing any small contributions of LVAE emissions, and (iii) the agreement in global top-down and bottom-up industry estimates of total PFCs prior to 2002 (Wong et al., 2015). Hence, it is not recommended to backcast LVAE PFC emissions prior to 2006.

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[12] The fundamental factors that make LVAE emissions more prevalent in today's current smelting technologies were less significant prior to the *2006 IPCC Guidelines* (expert judgement). These factors include: higher anode current density (Amps per cm^2 anode surface) to maximise cell productivity, lower anode-cathode distance to minimise cell voltage and hence energy use, larger anode dimensions which reduced the volume of liquid electrolyte to dissolve alumina, greater demand on transporting alumina to all anodes per point feeder (for PFPB technologies), and longer cells with significantly more anodes increasing the risk of localised issues in cells. These trends in the industry have occurred not only from the uptake of new technologies (e.g. from $PFPB_L$ to high amperage $PFPB_M$), but also through incremental upgrades *within* the same technology class (e.g. modernising existing $PFPB_L$ technology) to enable greater metal productivity and reduced energy use. Examples of upgrades within the same technology include Coursol *et al.* 2011, Kalban *et al.* 2013, Tarcy *et al.* 2011, many of which also led to a reduction in HVAE emissions, making LVAE emissions more significant in comparison.

If Tier 3 coefficients are available, it is *good practice* to use these coefficients for past inventory periods instead of using Tier 1 coefficients. There are several issues that impact the uncertainty of Tier 3 PFC emission factors when extrapolated to past inventory periods. The factors presented in the previous section on high voltage anode effects are also applicable when estimating the possibility of extrapolating LVAE estimations outside of the measured EF period. It is particularly important to consider any significant change in the alumina feeding strategy as it can significantly impact the LVAE emission coefficient. Finally, the study performed by (Dion *et al.* 2018b) highlighted the importance of considering numerous facilities when estimating LVAE emissions using Tier 1 emission factors. Inventory compilers should therefore be aware of the limitations associated with the Tier 1 coefficients included in this guidance when applying it to a limited number of smelters, or when used for a single facility. This is driven by the high uncertainty of LVAE PFC emissions from individual smelters and the possible variability of these emissions related to different control process parameters between the different facilities.

Table 4.16d has been provided to facilitate the choice of the correct LVAE emission factor (EF) for time consistent inventories.

TABLE 4.16D (NEW)
SUMMARY OF WHICH GUIDELINES TO REFER TO, FOR TIME CONSISTENT PFC INVENTORIES

For estimation of:	Time frame		
	Prior to 2006	**2006 to 2019**	**2020 and beyond**
HVAE emissions	Refer to *2006 IPCC Guidelines* for methodology and adequate EF.	Refer to Table 4.16c from the *2019 Refinements* to select an appropriate year for the EF transition based on the cell technologies.	Refer to *2019 Refinement* for methodology and adequate EF.
LVAE emissions	LVAE considered immaterial due to the high levels of HVAE from smelters[1] during this period[1]. It is *good practice* not to report LVAE.	Refer to *2019 Refinement* for methodology and adequate EF.	Refer to *2019 Refinement* for methodology and adequate EF.

[1] (International Aluminium Institute 2018). Refer to footnote 1 on the previous page, for factors that have led to LVAE emissions becoming more prevalent in the aluminium industry following the time of the *2006 IPCC Guidelines*.

4.4.3 Uncertainty assessment for primary aluminium production

There are major differences in the uncertainty for PFC emissions depending on the choice of Tier 1, Tier 2, or Tier 3 methods. The differences in uncertainty resulting from choice of method for carbon dioxide emissions are much smaller than for PFC emissions. There is no basis for country or regional differences in emissions resulting from aluminium production other than the differences that result from the specific type of production technologies and work practices in use in the country or region. These differences are reflected in the calculation methodologies described above.

4.4.3.1 EMISSION FACTOR UNCERTAINTIES

Uncertainties for CO_2 emissions

The uncertainty in the emission factors for calculating carbon dioxide emissions from carbon anode or paste consumption should be less than ±5 percent for both the Tier 2 and Tier 3 methods, and less than ±10 percent for the Tier 1 method. The reactions leading to carbon dioxide emissions are well understood and the emissions are very directly connected to the tonnes of aluminium produced through the fundamental electrochemical equations for alumina reduction at a carbon anode and oxidation from thermal processes. Both of these fundamental processes producing carbon dioxide are included in process parameters routinely monitored at the production facilities, the net carbon consumed and/or paste consumption. The main source of uncertainty is in the net carbon consumed for Prebake technologies and paste consumption for Søderberg cells. These factors are both carefully monitored and are important factors in the economic performance of a facility. Improvements in accuracy of carbon dioxide emissions inventories can be achieved by moving from Tier 1 to Tier 2 methods because there is a range of performance of reduction facilities in the consumption of carbon anode materials. Less significant improvements in accuracy can be expected in choosing the Tier 3 method over the Tier 2 method. This is because the major factors in the calculation are the net anode carbon consumed or paste consumption and the production of aluminium. The uncertainty of both these components of the calculation equation is low, 2 to 5 percent, and these uncertainties dominate the overall calculation of carbon dioxide emissions in the Tier 2 and Tier 3 methods. Facility specific data are used in both Tier 2 and Tier 3 calculations for these parameters. The Tier 3 method refines the calculation to use actual composition of the carbon anode materials. While there can be considerable variability in the minor components of the anode materials this variability does not contribute significantly to the overall calculation of carbon dioxide emissions.

Uncertainties for PFC emissions

In considering changes in uncertainty in PFC emissions inventory when moving from Tier 1 to Tier 2 and Tier 3 methods, there are major reductions in uncertainty when choosing the Tier 2 or Tier 3 methods over the Tier 1 method.

For HVAE emissions, the high level of uncertainty in the Tier 1 method reflects the significant variability in HVAE performance from one facility to another within the same technology class. The Tier 1 method is based on using a single default coefficient for all operators by technology type. Since there can be variations in anode effect performance (frequency and duration) by factors of 10 among operators using the same technology (IAI, 2005c), use of the Tier 1 method can result in uncertainties of the same magnitude. There is less impact on uncertainty levels in choosing the Tier 3 methods ($3a_{HVAE}$ and $3b_{HVAE}$) over the Tier 2 methods (2a and 2b) for estimating HVAE. When using the Tier 2a or 2b methods , the level of uncertainty reduction depends on the cell technology type. For example, the uncertainty for Tier 2a industry slope coefficients for individual facilities ranges from -27 to +32 percent for $PFPB_M$, to -53 to +130 percent for VSS. Compared to Tier 2a, the Tier 2 method provides significantly lower levels of uncertainty (roughly 3-5 times less, expert opinion) for individual facilities in terms of estimated PFC emissions; however again, the level of uncertainty depends on technology type.

Both Tier 2 (2a and 2b) and Tier 3 ($3a_{HVAE}$ and $3b_{HVAE}$) methods are based on direct PFC measurements that establish a relationship between HVAE performance and PFC specific emissions. The Tier 2 methods use average equation coefficients by technology while the Tier $3a_{HVAE}$ and $3b_{HVAE}$ methods uses facility-specific coefficients based on direct PFC measurements made at the facility. The lowest uncertainty for PFC emissions calculations from HVAE is from the use of the Tier $3b_{HVAE}$ method, followed by the Tier $3a_{HVAE}$ method. However, to achieve this lower uncertainty in Tier 3 PFC calculations it is important to use *good practices* in making facility specific PFC measurements. These measurement *good practices* have been established and documented in a protocol available globally (US Environmental Protection Agency & International Aluminium Institute 2008); it is *good practice* to check for updates to these protocols. When properly established these Tier 3 coefficients will have an uncertainty of +/-15 percent at the time the coefficients are measured.

For LVAE emissions, there is a high level of uncertainty associated with emission estimates using Tier 1. The Tier 3_{LVAE} method has a much lower uncertainty than Tier 1 as it is facility specific and based on a period of direct measurement at the site. LVAE is a relatively new discovery in the aluminium industry and as such, research continues on the best predictors and models to use to estimate LVAE emissions. There is also high variability observed between different facilities which results in large uncertainty ranges for the measured data that underpins the emissions factors. A measurement protocol for LVAE measurements to support the Tier 3_{LVAE} methodology is still under development and it is expected that such industry guidance to align measurement procedures and processes will improve consistency across the industry. Furthermore, considering the typically low concentrations of LVAE emissions and the detection limits of measuring instruments, it is expected that the uncertainty of the Tier 3_{LVAE} method for LVAE emissions will be larger than that fore Tier 3 methods ($3a_{HVAE}$ and $3b_{HVAE}$) to estimate HVAE emissions. Finally, while Tier 3_{LVAE} provides the lower uncertainty for LVAE estimations than Tier 1, the lowest overall uncertainty for total PFC emissions is from the Tier 3_{DM} method, i.e. direct measurement of total PFCs.

For CSU emissions, there is no specific methodology at the Tier 1 level, since CSU emissions are implicitly included in Tier 1 methods for estimating HVAE and LVAE emissions. However, given the wide variation in cell technologies and start-up operating practices from one facility to another, a higher level of uncertainty is expected at Tier 1 (as discussed previously for HVAE and LVAE emissions). If CSU emissions are accounted for separately, use of the Tier 2b method is likely to provide lower uncertainties compared to the Tier 2a method (with standard slope coefficients, which may overestimate HVAE emissions). Similarly, when facility-specific at Tier 3 coefficients are available, use of the Tier $3b_{HVAE}$ method is expected to provide lower levels of uncertainty than the Tier $3a_{HVAE}$ method. However, lowest uncertainties can be obtained through use of one of the following: (a) Tier $3a_{HVAE}$ or Tier $3b_{HVAE}$ emission coefficients for HVAE emissions, combined with Tier 3_{LVAE} coefficients determined specifically for CSU periods, or (b) use of Tier 3_{CSU} total emission factors determined specifically for CSU periods.

Finally, the Tier 3_{DM} direct measurement method, following industry best practices, provides the lowest of uncertainty level for all accounting methods for all PFC emissions (HVAE, LVAE and CSU), since the only sources of uncertainty is related to sampling procedures and measurement error.

4.4.3.2 ACTIVITY DATA UNCERTAINTIES

There is very little uncertainty in the data for the annual production of aluminium, less than 1 percent. The uncertainty in recording carbon consumption as baked anode consumption or coke and paste consumption is estimated to be only slightly higher than for aluminium production, less than 2 percent. For HVAE PFC emissions, the other component of calculated facility specific emissions using Tier 2a or Tier $3a_{HVAE}$ methods is the overall anode effect activity data, i.e.: anode effect minutes (AEM) per cell day for the slope method, or anode effect overvoltage (AEO) for overvoltage method. These parameters are typically logged by the process control system as part of the operations of nearly all aluminium production facilities and the uncertainties in these data are low. It also applies to the Tier 2b and $3b_{HVAE}$ approach where potline current and AED for individual HVAEs are precisely monitored by the cell control system; the only exception are cases where this individual AED data is automatically consolidated into overall anode effect performance statistics by the facility's software on a daily basis, or for different periods, which prevents the use of this method. Further activity data required for Tier 2b or $3b_{HVAE}$ method (Dion *et al.* approach) is the average daily metal production per cell, which has very little uncertainty in the data, less than 5 percent. For estimation of CSU emissions using the Tier 3_{CSU} method, there is very little uncertainty on the recorded number of cell start-ups (N_{CSU}) per accounting period, less than 2 percent.

4.4.4 Quality Assurance/Quality Control (QA/QC) Reporting and Documentation for primary aluminium production

4.4.4.1 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

It is *good practice* at all primary aluminium production facilities to maintain records of all of the necessary activity data to support calculations of emissions factors as suggested in these guidelines. These records will include production of aluminium, anode effect performance and consumption of carbon materials used in either Prebake or Søderberg cells. In addition, the International Aluminium Institute maintains global summaries of aggregated activity data for these same parameters and regional data are available from regional aluminium associations. It is *good practice* to aggregate emissions estimates from each smelter to estimate total national emissions. However, if smelter-level production data are unavailable, smelter capacity data may be used along with aggregate national production to estimate smelter production.

It is *good practice* to verify facility CO_2 emission factors per tonne aluminium by comparison with the expected range of variation that would be predicted from the variation noted in Tables 4.10 and 4.11 for carbon dioxide specific emissions. Also, the underlying equation coefficients used for calculating PFC emission factors per tonne aluminium should be compared with those noted. It is suggested that any inventory value outside the 95 percent confidence range of the data population variance be confirmed with the data source.

Use of standard measurement methods improves the consistency of the resulting data and knowledge of the statistical properties of the data. For HVAE emissions from primary aluminium, the '*EPA/IAI Protocol for Measurement of Tetrafluoromethane (CF_4) and Hexafluoroethane (C_2F_6) Emissions from Primary Aluminum Production'* is the internationally recognized standard (US Environmental Protection Agency & International Aluminium Institute 2008). Significant differences between calculated Tier $3a_{HVAE}$ or $3b_{HVAE}$ coefficients based on PFC measurements and the respective industry average Tier 2a or 2b coefficients for similar reduction technology should elicit further review and checks on calculations. Large differences should be explained and documented. The International Aluminium Institute (IAI) collects anode effect performance data from a number of smelters and can be consulted for assistance in identifying outlier data. . In addition, an up-to-date database of PFC measurements is also maintained by IAI and should be consulted when assessing the appropriateness of reported data. For LVAE emissions measurements which are relatively new and as yet, not widely measured, protocols are under development to improve consistency and alignment across the industry. Industry associations such as the IAI can be consulted for the latest developments.

Inter-annual changes in emissions of carbon dioxide per tonne aluminium should not exceed +/-10 percent based on the consistency of the underlying processes that produce carbon dioxide. In contrast, inter-annual changes in emissions of PFCs[13] per tonne of aluminium may change by values of up to +/- 100 percent. Increases in PFC specific emissions can result from process instability. Increases in anode effect frequency and duration can be the result of factors such as unanticipated power interruptions, changes in sources of alumina feed materials, cell operational problems, and increases in potline amperage to increase aluminium production. Decreases in PFC specific emissions can result from decreases in anode effect frequency and duration due to changes in the computer algorithms used in cell process control, upgrades in cell technology such as the installation of point feeders, improved work practices and better control of raw materials.

4.4.4.2 REPORTING AND DOCUMENTATION

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Volume 1, Chapter 6, Quality Assurance and Quality Control, Internal Documentation and Archiving. Some examples of specific documentation and reporting relevant to this source category are provided below.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced. To improve transparency, it is *good practice* to report emissions for PFCs from aluminium production separately from other source categories. Additionally, it is *good practice* that CF_4 and C_2F_6 emissions are reported separately on a *mass basis*.

The supporting information necessary to ensure transparency in reported emissions estimates is shown in Table 4.17, *good practice* Reporting Information for PFC Emissions from Aluminium Production by Tier, below.

Much of the production and process data are considered proprietary by operators, especially where there is only one smelter in a country. It is *good practice* to exercise appropriate techniques, including aggregation of data, to ensure protection of confidential data.

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[13] Reference to PFCs from this section applies to both HVAE and LVAE emissions.

TABLE 4.17 (UPDATED)
***GOOD PRACTICE* REPORTING INFORMATION FOR CALCULATING CO_2 AND PFC EMISSIONS FROM ALUMINIUM PRODUCTION BY TIER**

Data	Tier 1	Tier 2		Tier 3				
		2a HVAE	2b HVAE	3a HVAE	3b HVAE	3_{LVAE}	3_{CSU}	3_{DM}
PFCs (CF_4, C_2F_6 reported separately on mass basis)								
Annual national production (by technology)	X							
Annual production by smelter (by technology)		X		X		X		
Daily average production by smelter (by technology)[1]			X		X			
Annual current efficiency by smelter (by technology)[2]				X				
Anode Effect Minutes per cell-day		X		X				
Anode Effect Overvoltage (mV)				X				
Anode Effect Duration for individual HVAE by smelter[3]			X		X			
Line amperage (kA) during individual HVAE by smelter[3,4]			X		X			
Number of cell start-ups by smelter							X	
Default technology emission coefficients	X							
Technology specific emission coefficients linked to HVAE performance		X	X					
Facility specific emission coefficients linked to HVAE performance				X	X			
Facility specific emission coefficients linked to LVAE performance						X		
Facility specific emission coefficients linked to cell start-up							X	
Facility specific emission mass by direct measurement								X
Supporting documentation	X	X	X	X	X	X	X	X
CO_2								
Annual national production (by Prebake or Søderberg technology)	X							
Annual production by smelter (by Prebake or Søderberg technology)		X		X				
Net anode consumption for Prebake cells or paste consumption for Søderberg cells		X		X				
Carbon material impurity levels and carbon dust for Søderberg cells				X				

Notes:

[1] Daily average production data is only used in the Tier 2b/3b Dion *et al.* method, but not required for the Marks & Nunez method.

[2] Current efficiency data used only in the Tier 3a Overvoltage Method, but not required for Tier 3a Slope Method.

[3] Given the total number of HVAEs that occur in a facility annually, it is not practical to report to individual anode effect data for all HVAEs by smelter in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

[4] Line current data are only used in the Tier 2b/3b Marks & Nunez method, but not required for the Dion *et al.* method.

4.4.5 Methodological issues for alumina production

This guidance does not consider any new methodological issues associated with GHG emission inventories for the production of alumina from the conventional Bayer process. Emissions from the Bayer process are covered by existing guidance for fossil fuel combustion (Volume 2, Chapter 2) and for lime production (Volume 3, Section 2.3).

Methodological issues for alumina production from *Bayer-sintering parallel* (BSP*), Bayer-sintering sequential* (BSS) and *Nepheline processing* (NP) only are considered in this section (see Figure 4.12b). In 2017, only around 3 percent of alumina was produced globally via the Bayer-sintering process and around 1 percent via the Nepheline processing mainly in 3 countries – Russia, Kazakhstan and China.

4.4.5.1 ALTERNATIVE ALUMINA REFINING PROCESSES

BAYER-SINTERING PROCESS

The Bayer-sintering process is an alternative process to the more conventional Bayer process and is used when the bauxite feed has a high silica content making processing by the conventional Bayer process uneconomical due to high soda and alumina loss. The Bayer-sinter process involves a sintering stage (either with soda or with soda and limestone) that produces a solid sodium aluminate sinter which is then leached to form the sodium aluminate liquor (green liquor).

The process to produce green liquor is an alternative process to bauxite digestion which takes place in the conventional Bayer process. Green liquors from both Bayer and sintering branches of the process are cooled and held in precipitator vessels which results in the precipitation of alumina hydrate that is filtered and washed.

The alumina hydrate is then passed through a rotary or stationary calciner at 1100°C to drive off the chemically combined water. The result is a white powder, pure calcined or 'metallurgical' grade alumina (Al_2O_3), which is the basic raw material for primary aluminium production.

Depending on bauxite quality there two variations of the Bayer-sintering process: *parallel* and *sequential*. In the case of the *parallel* process (BSP), a proportion of the bauxite feed (up to 20-30 percent) is processed in the sintering branch and the rest is effectively processed by the conventional Bayer process (Figure 4.12b). In the case of *sequential* process (BSS), all bauxite is Bayer digested and red mud is mixed with soda and limestone and fed to the sintering operation to recover soda and alumina from it.

The main sources of the greenhouse gases emissions of CO_2, N_2O and CH_4 from the Bayer-sintering process are listed below, of which, the sintering step is the main focus of this section:

- Sintering (fuel combustion[14] and carbonates decomposition[15]);
- Power and heat production facilities (fuel combustion[1]);
- Alumina hydrate calcination (fuel combustion[1]);
- Lime calcination (fuel combustion and carbonates decomposition[16]).

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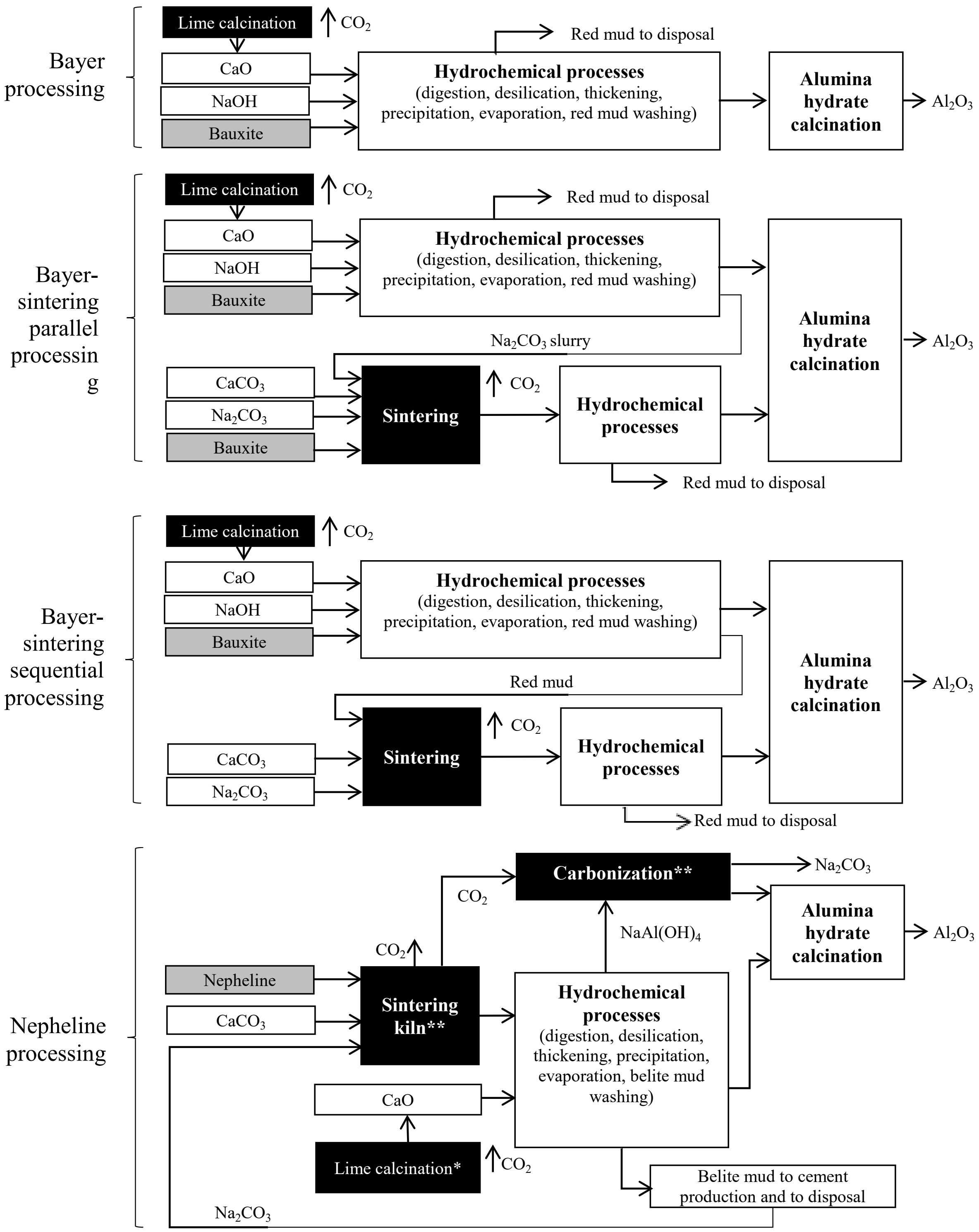
[14] Calculation of GHG emissions shall be done in accordance to Volume 2 Energy, Chapter 2 Stationary Combustion for Fuel Burning.

[15] Emissions from carbonate decomposition shall be calculated in accordance to Section 4.4.5.2 of current chapter.

[16] Calculation of GHG emissions shall be done in accordance to Volume 3 Industrial Processes and Product Use, Chapter 2 Mineral Industry Emissions, Section 2.3 Lime Production.

Figure 4.12b (New) Alumina production processes



* Calculated in accordance to Volume 3 Industrial Processes and Product Use, Chapter 2 Mineral industry emissions, Section 2.3 Lime production.

** Calculated in accordance to Section 4.4.5.2 of the current chapter.

NEPHELINE PROCESS

The *Nepheline process* (NP) is another alternative route for alumina production (<1 percent of global production[17] in 2017), which uses nepheline as the raw material as opposed to bauxite in the conventional Bayer process. Nepheline ore is a sodium and potassium containing aluminosilcate that contains more silica than alumina. In order to make silica insoluble at the leaching process, it is combined with lime forming $2CaO \bullet SiO_2$ (belite) using the sintering process. The belite mud may be used in the cement production whereas sodium and potassium streams may be used to produce soda ash and potash resulting in complex processing of nepheline raw material.

The main steps in the process are (refer to Figure 4.12b): crushing and milling of nepheline with limestone and recycled soda liquor forming the raw mix; and sintering of the raw mix (at about 1300°C) in rotary kilns where calcium carbonate is decomposed and the following reaction between calcium oxide and nepheline takes place, forming CO_2:

$$\boxed{4CaCO_3 + (Na,K)_2 O \bullet Al_2O_3 \bullet 2SiO_2 \rightarrow 2(Na,K)O \bullet AlO_2 + \ 2(2CaO,\ SiO_2) + 4CO_2}$$

The nepheline sinter is leached with the dissolution of alkali aluminate. The sinter residue is separated and transported to be used in cement production and the aluminate liquor is passed on for desilication to remove partially dissolved silica from the liquor. Then, alumina hydrate is obtained from the green liquor partly by decomposition and partly by carbonisation. Carbonisation captures CO_2 in the process (Figure 4.12b).

The main sources of greenhouse gases emissions from the nepheline process are similar to the Bayer-sintering process. To avoid double counting CO_2 emissions related to by-products produced alongside alumina (i.e. belite mud for cement, soda ash, potash), shall be considered only in relation to the raw materials required for the aluminium production process.

OTHER GHG SOURCES AND CAPTURE

CO_2 and CH_4 are also produced during other sub-processes that are implemented or may be implemented at all alumina refineries but the emissions from such processes are currently considered to be negligible and not a main source of GHG emissions (<1 percent, expert judgement).

Examples of such sub-processes include: flue gas desulphurization, acid cleaning of process equipment, organic carbon in bauxite, liquor burning, etc.

There are also a number of CO_2 capture pathways to consider:

- Carbonisation;
- CO_2 absorption through use of bauxite residue for flue gas desulphurization;
- CO_2 absorption through use of water collected from bauxite/nepheline storage residue area.

As noted throughout Volume 3 on Industrial Processes and Product Use (IPPU), the emission estimation methodologies outlined in this Chapter consider only process-related emissions and do not consider energy-related emissions. Inventory compilers should ensure that energy-related emissions are accounted for in the Energy Sector and that there is no double-counting of emissions between the Energy and IPPU Sectors. For example, the calculation of CO_2 emissions from fuel consumed in lime calcination, sintering, alumina hydrate calcination and electricity and heat production at a facility's own boilers, CHP or power plants should be considered using the guidance related to the combustion of fossil fuels.

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[17] There is only a single alumina refinery that uses this technology (Russia) and estimate is based on its annual production as a proportion of total global alumina production.

CO_2 capture from Carbonisation in nepheline process

The main reactions of CO_2 capture by during the Carbonisation sub-process are:

Stage 1

$$NaAl(OH)_4 + CO_2 \rightarrow Al(OH)_3 \downarrow + NaHCO_3$$

Stage 2

$$2NaAl(OH)_4 + 2NaHCO_3 \rightarrow Na_2O \bullet Al_2O_3 \bullet 2CO_2 \bullet 4H_2O \downarrow + 2NaOH$$

$$2NaOH \ + \ CO_2 \rightarrow Na_2CO_3 + \ H_2O$$

Part of CO_2 after Sintering is passed through gas treatment facilities to remove particles and other harmful components and then forwarded to carbonisators, where the carbonisation reaction proceeds step by step. This is done in a two-stage process.

CO_2 absorption through use of circulating water collected from bauxite/nepheline storage residue area

If a refinery uses circulating water collected from bauxite/nepheline storage residue area, which contains a lot of sodium alkaline to treat flue gas to remove particles, SO_2 and other acid gases it should be assumed that the scrubbing system will also remove some CO_2 in the flue gas. The efficiency of CO_2 capture is very dependent on concentration of sodium alkaline in circulating water and type of scrubbing technology. If there is a lack of direct measurement data on CO_2/CO in flue gas where such scrubbing system is used, it is not recommended that CO_2 removal be considered in CO_2 calculations.

CO_2 absorption through bauxite residue neutralization

Carbonation of bauxite residue (red mud) can be carried out to utilize the capacity of this waste to capture CO_2 and in turn, the capacity of CO_2 to neutralize the highly alkaline red mud. The absorption of CO_2 is rapid and can be efficient if there is good contact between the residue and the CO_2. For high concentration CO_2 streams (90 percent or more) the reaction can be virtually 100 percent with a few seconds contact. Total alkalinity of red mud drops drastically with the added CO_2 recorded as an increase in bicarbonate alkalinity.

For lower concentrations of CO_2 such as flue gas where concentrations may be 12-15 percent, the reaction efficiency will be reduced. If CO_2 removal data is not available for bauxite residue contacted with gases containing less than 50 percent CO_2, then it is recommended that reaction efficiency of 35 percent be assumed by default.

CO_2 absorption can be estimated by multiplying the quantity of CO_2 injected into the process multiplied by the measured or assumed reaction efficiency.

Measurement of the increase in bicarbonate in the residue can also be used as a better measure of the amount of CO_2 actually absorbed in the neutralization process.

4.4.5.2 CHOICE OF METHOD FOR ALUMINA PRODUCTION

The decision tree in Figure 4.12c describes *good practice* in choosing the most appropriate method based on national circumstances.

In the Tier 1 method, emissions are estimated using alumina production data and national or default emission factors for the relevant technologies. The estimation of emissions directly from alumina production, without process specific information about raw materials and technology, is subject to high levels of uncertainty. This is because emissions from carbonates decomposition in the sintering and/or lime calcination processes can vary significantly.

Tier 2 implements method from Tier 1 but country-specific emission factors should be applied.

The Tier 3 approach relies on plant specific data. Tier 3 methods should also include a correction for emissions of dust. Tier 3 also includes a correction addition for emissions associated with dust not recycled to the kiln. Any uncalcined dust not recycled to the kiln should be subtracted from the total emissions estimate.

Should CO_2 capture technology be installed and used at a plant, it is *good practice* to deduct the CO_2 captured in a higher tier emissions calculation (Tier 3). The default assumption is that there is no CO_2 capture and storage (CCS) taking place. Any methodology taking into account CO_2 capture should consider that CO_2 emissions captured in the process may be both fuel combustion and process-related. In cases where combustion and process emissions are to be reported separately, e.g. for alumina production, inventory compilers should ensure that the same quantities of CO_2 are not double counted. In these cases, the total amount of CO_2 captured should preferably be reported in the corresponding energy combustion and IPPU source categories in proportion to the amounts of CO_2 generated in these source categories. For additional information on CO_2 capture and storage refer to Volume 3, Section 1.2.2 (under Industrial Processes and Product Use) and Volume 2, Section 2.3.4 (Under Energy).

TIER 1 METHOD FOR SINTERING

The Tier 1 method for lime production emissions is described in (Volume 3, Section 2.3.1.1). To avoid double counting, before applying this method it is essential to check whether lime production data from alumina plants is already considered in the inventory for lime production. If the lime production process at alumina plants has not been, included, the emissions associated with this process shall be considered as source related to alumina production. To attribute lime production emissions specifically to alumina production, it is necessary to gather data on how much of the national lime production occurs at alumina plants.

The Tier 1 method for the sintering process (including BSP, BSS and NP alumina production processes) is based on default emission factors, but requires country specific activity data on production mass produced by BSS, BSP and NP processes. If the Bayer-sinter (BS) process is used, the GHG emissions from the sintering are dependent on the quality of bauxite and the silica content of the bauxite. High silica content, low content of Al_2O_3 in ore leads to use of high carbonate content which results in greater GHG emissions. In case of Nepheline processing (NP), GHG emissions from the sintering are dependant on the Al_2O_3 content of the nepheline ore.

If detailed and complete data (including mass and composition) for the carbonates consumed in the sintering and lime production processes are not available, it is *good practice* to use aggregated national alumina production data, based on the technology applied, raw material and data on the proportion of Bayer and Bayer-sintering, expressed as an emission factor in the following Equation 4.27g:

EQUATION 4.27G (NEW)
TIER 1: SINTERING PROCESS EMISSIONS BASED ON ALUMINA PRODUCTION DATA

$$CO_2\ Emissions = M_{BS\_Al_2O_3} \bullet S_{BS} \bullet EF_{BS\_Sint} + M_{NP\_Al_2O_3} \bullet S_{NP} \bullet EF_{NP\_Sint} + M_{Lime} \bullet EF_{Lime}$$

Where:

CO_2 Emissions = emissions of CO_2 from sintering production, tonnes

M_{BS_Al2O3} = mass of alumina produced by BSP and BSS processes, tonnes

M_{NP_Al2O3} = mass of alumina produced by NP processes, tonnes

M_{Lime} = mass of lime produced, tonnes.

S_{BS} = mass fraction of alumina produced by sintering process (BSP and BSS). The parameter can be varied from 0 to 1, where 1 is related to 100 percent of alumina produced by sintering process. If there is no information about country specific mass fraction, 1 shall be used with assumption that 100 percent of alumina produced by sintering process.

S_{NP} = mass fraction of alumina produced by sintering process. The parameter equals 1, because 100 percent of alumina in the NP process is produced by sintering process.

EF_{BS_Sint} = default emission factor for sintering BSP and BSS processes, tonnes CO_2/tonne alumina (see discussion under Section 4.4.5.3 Choice of Emission Factors), which is not corrected for dust.

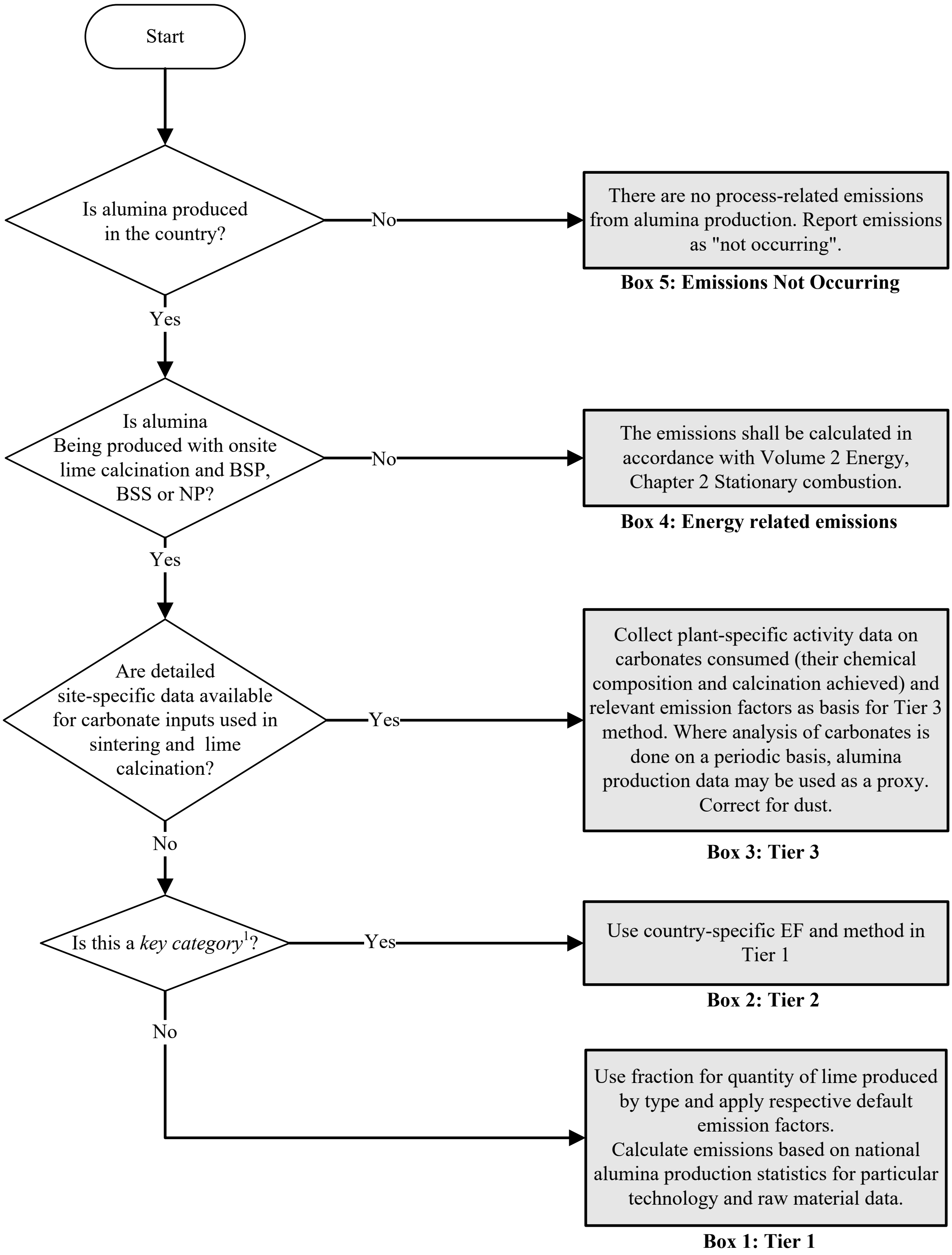
EF_{NP_Sint} = default emission factor for sintering NP process, tonnes CO_2/tonne alumina (see discussion under Section 4.4.5.3 Choice of Emission Factors), which is not corrected for dust.

EF_{Lime} = default emission factor for lime production, tonnes CO_2/tonne lime (Volume 3, Section 2.3.1.2)

The Tier 1 approach is based on the following assumptions about the alumina production and sintering process:

- The mass fraction of alumina produced by sintering process (rather than the leaching process) is stable over time;
- In case of alumina production from the nepheline ore, 100 percent of alumina is produced with the sintering process;
- Plants are generally able to control the $CaCO_3$ content of the raw material inputs and output of sintering process within close tolerances;
- The $CaCO_3$ content of the raw materials inputs from a given plant tends not to change significantly over time;
- The main source of the CaO for most plants is $CaCO_3$ and, at least at the plant-specific level, any major non-carbonated sources of CaO are readily quantified (see Section 4.4.5.3 below);
- A 100 percent (or very close to it) calcination factor is achieved for the carbonate inputs for sintering output, including (commonly to a lesser degree) material lost to the system as non-recycled dust; and
- Dust collectors at plants capture essentially all of the dust;
- The capture of CO2 cannot be quantified and assumed to be zero.

Figure 4.12c (New) Decision tree for estimation of CO_2 emissions from alumina production



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.

TIER 2 METHOD FOR SINTERING

The Tier 2 method is a country specific method. This uses the same approach to Tier 1 in accordance with Equation 4.27g, but with regional or country specific emissions factors for calculation of CO_2 from sintering, instead of default emission factors.

TIER 3 METHOD FOR SINTERING: USE OF CARBONATE INPUT DATA

Where national level data for lime production at alumina refineries are available on the types of lime produced, it is *good practice* to estimate emissions using a Tier 3 approach described in of Chapter 2, Section 2.

For sintering processes, CO_2 emissions are calculated using a mass balance approach that considers the carbonates and carbon content of input and output materials. Carbonates of input materials are destroyed due to high temperatures in sintering kilns. The Tier 3 method uses actual concentrations of impurities.

Tier 3 is based on the collection of disaggregated data on the types (compositions) and quantities of carbonates consumed in the sintering process at a particular plant, as well as the respective emission factors of the carbonates consumed. Emissions are then calculated using Equation 4.27h. The Tier 3 approach includes an adjustment to subtract any uncalcined carbonate within sintering kiln dust (SKD) that is not returned to the kiln. If the SKD is fully calcined, or all of it is returned to the kiln, this SKD correction factor becomes zero. Tier 3 is still considered to be *good practice* in instances where inventory compilers do not have access to data on uncalcined SKD. However, excluding uncalcined SKD may result in slightly overestimated emissions.

Limestones and shales (raw materials) may also contain a proportion of organic carbon (kerogen), and other raw materials (e.g., fly ash) may contain carbon residues, which would yield additional CO_2 when burned. These emissions typically are not accounted for in the Energy Sector, but if carbon-containing raw materials are used extensively, inventory compilers should endeavour to see if they are included in the Energy Sector. Currently however, there is insufficient data on the kerogen or carbon contents of non-fuel raw materials for mineral processes to allow a meaningful default value related to the average kerogen content of raw materials to be provided in this chapter. For plant-level raw material-based calculations (Tier 3) where the kerogen content is high (i.e., contributes more than 5 percent of total heat), it is *good practice* to include the kerogen contribution to emissions.

The Tier 3 approach will likely only be practical for individual plants and countries that have access to detailed plant-level data on the carbonate raw materials. Emissions data collected at the plant level should then be aggregated for purposes of reporting national emissions estimates. It is recognized that frequent calculations of emissions based on direct analysis of carbonates could be burdensome for some plants. As long as detailed chemical analyses of the carbonate inputs are carried out with sufficient frequency to establish a good correlation between the carbonates consumed at the plant level and the resulting alumina production, the sinter output may then be used as a proxy for carbonates for emissions calculations in the intervening periods. That is, a plant may derive a rigorously-constrained emission factor for the plant's alumina, based on periodic calibration to the carbonate inputs and outputs.

EQUATION 4.27H (NEW)
TIER 3: EMISSIONS BASED ON CARBONATE RAW MATERIAL INPUTS TO THE SINTERING KILN

$$CO_2\ Emissions = \sum_i \left(M_{oi} \bullet C_{iCO_2}\right) + E_{LC} + EF_s \bullet M_s + (0.71\ C_{Na_2O} \bullet V_s)\ /\ 1000$$
$$-\ E_{sp} - E_{rm} - E_{SKD} + E_{nf} - E_{cc}$$

Where:

CO_2 Emissions = total emissions of CO_2 from sintering kiln, tonnes

$\Sigma_i\ (M_{oi} \bullet C_{iCO2})$ = CO_2 emissions from carbonates in bauxite or nepheline ore decomposed in kiln, tonnes

M_{oi} = mass of *i* ore recalculated per dry conditions consumed in the kiln, tonnes

$C_{i}co_2$ = the weighted average content of CO_2 in *i* bauxite (nepheline) ore according to chemical analysis and assumption that 100 percent calcination will be achieved (in the absence of chemical analysis results, the content of CO_2 in nephelines is determined as the difference in loss on ignition and SO_3), as given by Equation 4.27k), fraction

E_{LC} = CO_2 emissions released from limestone calcination, tonnes CO_2. The calculation shall be done in accordance to Tier 3 approach described in Volume 3 IPPU, Chapter 2, Section 2.3. To avoid double counting before applying this method it is necessary to check if limestone usage data from alumina plant is already considered at national level and CO_2 emissions from lime calcination are already considered in lime production data. If limestone usage for sintering process at alumina plants has not been considered at national level, this process shall be considered as source related to alumina production emission. If the emissions are considered as lime calcination emissions they shall be removed from calculations by this formula.

$EF_s \bullet M_s$ = CO_2 emissions from soda carbonate decomposition, tonnes. To avoid double counting before applying this method it is necessary to check if this source is already considered at national level. If soda decomposition in sintering process at alumina plants has not been considered at national level, this process shall be considered as source related to alumina production emission. If the emissions accounted for in Volume 3 (under Industrial Processes and Product Use), Chapter 2 (Mineral Industry Emissions), Section 2.5 (Other Process Uses of Carbonates) they shall be removed from calculations by this formula.

EF_s = emission factor for soda carbonate forwarded to the kiln with ore, tonnes CO_2 / tonnes soda carbonate (see Table 2.1 Chapter 2 Mineral Industry emissions)

M_s = mass of soda forwarded to the kiln with ore, tonnes

$(0.71\ C_{Na2O} \bullet V_s) / 1000$ = CO_2 emissions from the decomposition of soda contained in a soda solution, tonnes

0.71 = stoichiometric conversion factor of CO_2 from Na_2O. Na_2O is measure in the soda solution

C_{Na2O} = concentration of sodium oxide (carbonate) in the soda solution, forwarded to the kiln, g/L

V_s = volume of soda solution, m^3

E_{sp} = CO_2 emissions captured during Carbonisation process and contained in produced sodium carbonate, tonnes CO_2 (as given by Equation 4.27i)

E_{rm} = Potential CO_2 emissions based on the mass of carbon in bauxite or nepheline residue, that is not emitted because some carbon absorbed by residue and stored at bauxite or nepheline residue areas, tonnes (refer to Equation 4.27l)

E_{SKD} = CO_2 emissions from un-calcined SKD not recycled to the kiln, tonnes (refer to Equation 4.27j)

E_{nf} = CO_2 emissions from carbon-bearing non-fuel materials (as given by Equation 4.27m), tonnes

E_{cc} = CO_2 absorption through use of circulating water collected from bauxite/nepheline storage residue area and/or absorption through bauxite residue neutralization (as given by Equation 4.27n), tonnes

EQUATION 4.27I (NEW)
EMISSIONS CAPTURED DURING CARBONISATION PROCESS AND CONTAINED IN PRODUCED SODIUM CARBONATE

$$E_{sp} = EF_s \bullet M_{sout}$$

Where:

E_{sp} = CO_2 emissions captured during Carbonisation process and contained in produced sodium carbonate, tonnes

EF_s = emission factor for soda carbonate forwarded to the kiln with ore tonnes CO_2 / tonnes soda carbonate (see Table 2.1 Chapter 2 Mineral Industry emissions)

M_{sout} = mass of soda produced for using out of plant, tonnes

EQUATION 4.27J (NEW)
EMISSIONS FROM UN-CALCINED SKD NOT RECYCLED TO THE KILN

$$E_{SKD} = \left(\left(M_{dr} + M_{dnr} \right) \bullet E_{ac} / 100\% - M_{dr} \right) \ \bullet C_{CO_2}$$

OR

$$E_{SKD} = \left(M_d \bullet E_{ac} / 100\% - M_{dr} \right) \ \bullet C_{CO_2}$$

Where:

E_{SKD} = CO_2 emissions from un-calcined SKD not recycled to the kiln, tonnes

M_{dr} = mass of SKD recycled to the kiln, tonnes

M_{dnr} = mass of SKD not recycled to the kiln (= ‘lost’ SKD), tonnes

M_d = mass of SKD forwarding to exhausted gases cleaning facilities at sintering kilns, tonnes

E_{ac} = efficiency of exhausted gases cleaning facilities at sintering kilns, percentage

C_{CO2} = carbon content in dust recalculated in CO_2, fraction

EQUATION 4.27K (NEW)
WEIGHTED AVERAGE CONTENT CO_2 IN ‘*I*’ BAUXITE (NEPHELINE) ORE

$$C_{iCO_2} = \sum_j \left(EF_j \bullet M_j \right)$$

Where:

C_{iCO2} = the weighted average content of CO_2 in *i* bauxite (nepheline) ore according to chemical analysis, assuming 100 percent calcination of the carbonate, fraction

EF_j = emission factor for the particular carbonate *j*, tonnes CO_2 / tonnes carbonate (see Table 2.1 Chapter 2 Mineral Industry emissions)

M_j = mass fraction of carbonate *j* consumed in the kiln, fraction

EQUATION 4.27L (NEW)
POTENTIAL EMISSIONS FROM BAUXITES (NEPHELINES) RESIDUE

$$E_{rm} = 44/12 \bullet M_{br} \bullet C_c$$

Where:

E_{rm} = Potential CO_2 emissions based on the mass of carbon in bauxite or nepheline residue, that is not emitted because some carbon absorbed by residue and stored at bauxite or nepheline residue areas, tonnes

M_{br} = mass of dry bauxite or nepheline residue disposed, tonnes

C_c = mass fraction of C in dry bauxite or nepheline residue, fraction

EQUATION 4.27M (NEW)
EMISSIONS FROM CARBON-BEARING NON-FUEL MATERIALS

$$E_{nf} = \sum_k \left(M_k \bullet X_k \bullet EF_k \right)$$

Where[18]:

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[18] The ignored CO_2 emissions from non-carbonate carbon (e.g., carbon in kerogen, carbon in fly ash) in the non-fuel raw materials can be considered negligible if the heat contribution from kerogen or other carbon is < 5% of total heat (from fuels).

E_{nf} = CO_2 emissions from carbon-bearing nonfuel materials, tonnes

M_k = mass of organic or other carbon-bearing non-fuel raw material *k*, tonnes

X_k = fraction of total organic or other carbon in specific non-fuel raw material *k*, fraction

EF_k = emission factor for kerogen or other carbon-bearing nonfuel raw material *k*, tonnes CO_2/tonne carbon-bearing nonfuel raw material

EQUATION 4.27N (NEW)

CO_2 ABSORPTION THROUGH USE OF CIRCULATING WATER COLLECTED FROM BAUXITE/NEPHELINE STORAGE RESIDUE AREA AND/OR ABSORPTION THROUGH BAUXITE RESIDUE NEUTRALIZATION

$$E_{cc} = Vgas \bullet C_{CO_2} \bullet D_{CO_2} \bullet GTE_{CO_2} / 100$$

Where:

E_{cc} = CO_2 absorption through use of circulating water collected from bauxite/nepheline storage residue area and/or absorption through bauxite residue neutralization, tonnes

Vgas = exhaust gas volume forwarded to exhaust gas treatment facility, cubic meters

Cco_2 = CO_2 concentration in exhaust gas (instrumental measures), fraction of volume

Dco_2 = CO_2 destiny under normal conditions, tonne/cubic meters

$GTEco_2$ = exhaust gas treatment facility efficiency (instrumental measures), percentage

4.4.5.3 CHOICE OF EMISSION FACTORS FOR ALUMINA PRODUCTION

Emissions factors for Sintering can be chosen based on available data. In the case that site-specific data is not available, Tier 1 default emission factors can be used. Emissions factors for lime production are provided in Volume 3, Section 3.3.1.2.

TIER 1 METHOD FOR SINTERING

The implementation of sintering processes is determined by bauxite quality (alumina content), carbonates and silica content in the ore which can vary significantly. Based on existing process data from operating plants, Tier 1 emissions factors were derived for Bayer-sintering processes and the nepheline-sintering process (NP), to be applied in Equation 4.27g (see Table 4.17a). For Bayer-sintering process Tier 1 emissions factors can be applied for both parallel (BSP) and sequential (BSS) processes.

TABLE 4.17A (NEW)

TECHNOLOGY SPECIFIC DEFAULT EMISSION FACTORS FOR THE CALCULATION OF CO_2 EMISSIONS FROM ALTERNATIVE SINTERING PROCESSES (TIER 1 METHOD)

Technology	$EF_{SintAl2O3}$ (tonne CO_2/tonne Al)[a]	Uncertainty Range (%)[b]
Bayer-sintering (BSP and BSS)	0.81	-8/+4
Nepheline-sintering process (NP)	2.46	-2/+4

[a] The defaults based on the following process data – alumina content (Al_2O_2) is 45.8% in bauxites and 26.2% in nepheline ore. Bauxite and nepheline consumption in sintering is very depend on Al_2O_2 content and in case of poor ore where Al_2O_2 content is out of range EF shall be higher and uncertainty level will increase.

[b] Uncertainty range is based on calculations from alumina plants that operate sintering kilns for several years based on alumina content as described above.

TIER 2 METHOD FOR SINTERING

Country-specific emission factors should be collected based on knowledge of technologies (technological routes) implemented at a country's facilities and also based on data for lime (country-specific carbon content). Tier 1 method then should be applied.

If alumina plants have sintering processes, site specific data should be obtained relating to the volume of alumina production, percent of alumina produced with sintering. Plant specific volume of alumina production, percentage of alumina produced with sintering and information about the bauxite sources or technology and country specific emissions factors shall be calculated and should be provided for each national-level GHG emissions calculation campaign.

TIER 3 METHOD FOR SINTERING

The Tier 3 emission factors are based on the actual CO_2 content of the carbonates present (see Equation 4.27h in this chapter and Table 2.1 of Volume 3, Chapter 2 Mineral Industry Emissions).). The Tier 3 approach requires the full accounting of carbonates (species and sources).

CO_2 emissions captured by other CO_2 capturing technologies can be calculated using site specific data only. Where such data is unavailable, CO_2 emissions captured do not considered in CO_2 emissions calculation.

If there is no site-specific data for mass of carbon in bauxite or nepheline residue, the following data can be used as worldwide figures:

- CO_2 in bauxite and nepheline residue 1 percent of dry content with a ± 50 percent uncertainty range[19].

Emissions correction factor for sintering kiln dust (SKD)
Dust may be generated at various points in the kiln line apparatus used for sintering. The composition of this dust can vary depending on where it is generated but all may be included under the term 'sintering kiln dust' (SKD). SKD includes particulates derived from the raw materials, and the original carbonate component of the dust may be incompletely calcined. SKD can be efficiently captured by dust control technology and then recycled to the kiln (the preferred practice), or it may be directly returned to the kiln in the combustion air, or it may be disposed of after capture. The degree to which SKD can be recycled to the kiln depends on various considerations and usually 100 percent of collected dust are returned to the kiln. Any SKD not recycled to the kiln is considered to be 'lost' to the process and emissions associated with it will not be accounted for in the sintering process. To the degree that the lost SKD represents calcined carbonate raw materials, the emissions from these calcined raw materials represent a subtraction in the Tier 3 calculation. The kiln dust may consist of dust from raw materials as well as dust from the burning of liquid or solid fuels. In that case where combustion and process emissions are to be reported separately, e.g. for alumina production, it is *good practice* for inventory compilers ensure that the carbon in the dust related to fuel combustion is not double counted. In these cases, the total amount of C in the dust from fuel burning should preferably be extracted from IPPU source categories in proportion to the amounts of CO_2 generated in these source categories.

4.4.5.4 CHOICE OF ACTIVITY DATA

TIER 1 METHOD

In Tier 1, national-level data should be collected only for those plants where lime calcination processes are part of alumina production process. However, calcined lime purchased from other producers should not be considered to avoid double counting.

If a proportion of calcined lime is produced for uses other than alumina production, to avoid double counting CO_2 emissions from carbonates decomposition at the lime calcination kiln shall be related to alumina production in the proportion of lime used for alumina production only. CO_2 emissions related to other uses of calcined lime shall be reported as emissions related to lime calcination described at Chapter 2 Section 2.3. The detailed information about choice of activity data for lime production please refer to Section 2.3.1.3 in Volume 3, Chapter 2.

If alumina plants have sintering processes, site specific data should be obtained relating to the volume of alumina production, percent of alumina produced with sintering. Plant specific volume of alumina production, percentage

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[19] The uncertainty range is based on expert judgment.

of alumina produced with sintering and information about the bauxite sources or technology should be provided for each national-level GHG emissions calculation campaign.

TIER 2 METHOD

In Tier 2, national-level data should be collected only for those plants where sintering/lime calcination processes are part of alumina production process. However, calcined lime purchased from other producers should not be considered to avoid double counting.

TIER 3 METHODS

For lime production process refer to Section 2.3.1.3 Choice of Activity Data in Volume 3, Chapter 2.

The type of activity data required for Tier 3 is likely available only at individual plants. Any reporting entity using Tier 3 should ensure that all carbonate inputs (i.e., types, amounts, all sources) to the kiln are fully investigated as part of the initial implementation of the Tier 3 method, and the full investigation repeated whenever there is any significant change in materials or processes. After a full analysis of the carbonate inputs is completed, and assuming that no significant change in the composition of materials or production process takes place, it is consistent with *good practice* to develop a rigorous plant-specific emission factor based on the carbonate input analysis and apply that emission factor to sintering process. Subsequently, the sintering production data may then be used for the carbonate calculations to estimate emissions. To be consistent with *good practice*, this linkage should be periodically recalibrated.

In general, data related to carbonated input materials should be collected annually. However, it is likely that there could be a carbonate component within the mass of carbon in bauxite or nepheline residue, emissions from un-calcined SKD not recycled to the kiln, and perhaps some other fuels (emissions from carbon-bearing nonfuel materials). If, during the full investigation, it is determined that the amount of carbonates from non-major sources is small (e.g., less than 5 percent of total carbonate) the plant can apply a constant value for the minor source(s) in intervening years before the next full investigation. Recognizing that estimating activity data for these smaller sources may lead to analytical (and other) errors, it may be assumed for emission calculation purposes that the minor source of carbonate is $CaCO_3$, but this assumption should be transparently documented.

Activity data should exclude any carbonates that are not fed into the kiln.

4.4.5.5 COMPLETENESS

Alumina production data may be available in national statistical databases, or could be collected, if such data have not been published in national statistics.

Completeness is a particularly important issue to consider where plant specific data are used to estimate national emissions using Tier 3. Under Tier 3, it is important that all alumina plants with lime production and sintering processes are considered, and that all carbonates consumed in the sintering process are included in the emission calculation. Plants with bauxites/nephelines sintering processes are well identified in each country, but data on the fraction weight of carbonates consumed may not be readily available. In order for the Tier 3 method to be considered ‘complete’, all carbonates consumed must be recorded.

In countries where only a subset of plants with lime production and bauxites/nephelines sintering processes report data for the Tier 3 method, it may not be possible to report emissions using a Tier 3 for all facilities during the transition. Where data on the carbonate inputs are not available for all plants to report using Tier 3, it may be possible to determine the share of production represented by non-reporting plants and use this information to estimate the remaining emissions using Tier 1 in order to ensure completeness during the transition period.

The potential for double counting also should be considered. For example, it is *good practice* for inventory compilers to review statistics used to estimate emissions from the source category ‘Other Process Uses of Carbonates’ and ‘Lime production’ to ensure that emissions reported in that source category do not result from the use of these carbonates in alumina production. Where carbonates are used for alumina production, it is *good practice* to report the emissions under Alumina Production. Finally, inventory compilers should include only process-related emissions from alumina production in this source category. To avoid double-counting, it is *good practice* to account for combustion-related emissions in the Energy volume.

There is one additional issue that, while not included in the current methodology, may become relevant for consideration in the future. Sodium alkaline contained in bauxite/nepheline residue area can re-absorb atmospheric CO_2. However, the rate of carbonation is very slow (years to centuries).

4.4.5.6 DEVELOPING A CONSISTENT TIME SERIES

It is *good practice* to collect site specific data where possible for all inventory years. However, often it can be difficult to collate historic data for closures, closed operations or if significant changes in changes in technology or sourcing of bauxites/nephelines has taken place. In such cases, inventory compilers can consult industry experts to assist with extrapolation of CO_2 emission figures (e.g. normalization by volume of alumina production or based on applying of data from similar plants in the reporting country or average worldwide figures for similar technology). See also Chapters 2 and 5 of Volume 1 of *2006 IPCC Guidelines*.

For lime production, refer to Section 2.3.1.5 in Chapter 2.

4.4.6 Uncertainty assessment for alumina production

Uncertainty estimates for bauxite/nepheline sintering processes result predominantly from uncertainties associated with activity data, and to a lesser extent, from uncertainty related to the emission factor.

Uncertainty estimates for lime production is described at Section 2.3.2 Uncertainty assessment in Chapter 2 Volume 3 of 2006 *IPCC Guidelines*.

4.4.6.1 EMISSION FACTOR UNCERTAINTIES

For Tier 1, the major uncertainty component is associated with the emission factor for sintering.

For Tier 2 and 3, there is relatively little uncertainty associated with the emission factors of the source carbonates because they are based on plant specific data, stoichiometric ratios and mass balance approaches.

4.4.6.2 ACTIVITY DATA UNCERTAINTIES

The uncertainty for percentage of bauxite/nepheline processing at sintering process is moderate. The level of uncertainty is indicated in the Table. 4.17b. The uncertainty in data on alumina production tonnages is about 1 percent.

For Tier 3, the uncertainty in data on weight or mass of *i* ore recalculated per dry conditions consumed in the kiln tonnages, is about 1-2 percent. Collecting data from individual producers (if complete) rather than using national totals will reduce the uncertainty of the estimate because these data will account for variations in conditions at the plant level. Except for SKD the greatest sources of uncertainty associated with Tier 3 are the uncertainties associated with identification of carbonate species (1-5 percent) and the weight of raw materials.

Although emissions are much smaller than from carbonates, there may be considerable uncertainty associated with estimating emissions from SKD in Tier 3 if plants do not weigh the SKD that is not recycled to the kiln or if the plants lack SKD scrubbers. Where the weight and composition of SKD are unknown for a plant, the uncertainty will be higher. As an example, an estimate of the uncertainties for different factors is presented in equations 4.27h-4.27n. The uncertainties are presented in Table 4.17b and are approximate component uncertainties – that is, they are those associated with a particular operation or activity in the bauxite/nepheline processing at sintering process. In order to quantify uncertainty for bauxite/nepheline processing at sintering process, the default uncertainties provided in Table 4.17b should be combined.

TABLE 4.17B (NEW)
DEFAULT UNCERTAINTY VALUES FOR BAUXITE/NEPHELINE SINTERING PROCESSES

Uncertainty[a]	Comment	Tier
Chemical Analysis / Composition		
1-3%	Percentage of bauxite processing at sintering process	1
10%	Estimation of percentage of bauxite processing at sintering process	1
-2/+4%	Emission factor for sintering (NP)	1
-8/+4%	Emission factor for sintering (BSP and BSS)	1
10%	Assumption that emission factor for sintering is permanent over the years	1
5%	The content of sodium oxide (carbonate) in the soda solution, forwarded to the kiln	3
15%	Estimation of content of sodium oxide (carbonate) in the soda solution, forwarded to the kiln	3
5%	The weighted average content of C in dry bauxite/nepheline residue	3
50%	Estimation of weighted average content of C in dry bauxite/nepheline residue	3
1%	Weight or mass share of particular carbonate consumed in the kiln	3
2%	Fraction calcination achieved for carbonates	3
10-20%	Assumption 100% of fraction calcination achieved for carbonate	3
3%	Weight or mass of organic or other carbon-bearing nonfuel raw material	3
3%	Fraction of total organic or other carbon in specific nonfuel raw material	3
50%	Estimation of weight or mass of organic or other carbon-bearing nonfuel raw material	3
50%	Estimation of fraction of total organic or other carbon in specific nonfuel raw material	3
1-3%	Kerogen (or other non-carbonate carbon) determination	3
10%	CO2 concentration in exhaust gas	3
5%	Exhaust gas treatment facility efficiency	3
1%	CO2 destiny under normal conditions	3
Production Data		
1-2%	Reported (plant-level) alumina production data	1, 3
10%	Use of estimated country (or aggregated plant) production data (national statistics).	1
1-2%	Weight or mass of ore recalculated per dry conditions consumed in the kiln	3
10%	Estimation of weight or mass of ore recalculated per dry conditions consumed in the kiln	3
1-2%	Weight or mass of soda forwarded to the kiln with ore	3
10%	Estimation of weight or mass of soda forwarded to the kiln with ore	3
2%	Volume of soda solution	3
35%	Estimation of volume of soda solution	3
1-2%	Weight or mass of soda produced for using out of plant	3
5%	CO_2 emissions captured by other CO_2 capturing technologies	3
15%	Estimation of CO_2 emissions captured by other CO_2 capturing technologies	3
5%	Mass of bauxite/nepheline residue disposed	3
10%	Estimation of bauxite/nepheline residue disposed	3
2%	Exhaust gas volume forwarded to exhaust gas treatment facility	3

TABLE 4.17B (NEW) (CONTINUED)
DEFAULT UNCERTAINTY VALUES FOR BAUXITE/NEPHELINE SINTERING PROCESS

Uncertainty[a]	Comment	Tier
SKD		
1-2%	Weight or mass of SKD recycled to the kiln	3
10%	Estimation of weight or mass of SKD recycled to the kiln	3
1-2%	Weight or mass of SKD not recycled to the kiln	3
10%	Estimation of weight or mass of SKD not recycled to the kiln	3
1-2%	Efficiency of exhausted gases cleaning facilities at sintering kilns	3
10%	Estimation of efficiency of exhausted gases cleaning facilities at sintering kilns	3
1-2%	Carbon content in dust recalculated in CO_2	3
10%	Estimation of carbon content in dust recalculated in CO_2	3

[a] Uncertainty estimates are based on expert judgement.

4.4.7 Quality Assurance/Quality Control (QA/QC), Reporting and Documentation for alumina production

4.4.7.1 QUALITY ASSURANCE / QUALITY CONTROL (QA/QC)

In addition to the general guidance on QA/QC, specific procedures of relevance to this source category are outlined below.

COMPARISON OF EMISSIONS ESTIMATES USING DIFFERENT APPROACHES

Comparisons could be made between estimated emissions using different tiers. For example, if a bottom-up approach is used to collect activity data (i.e., collection of plant-specific data), then inventory compilers should compare the emissions estimates to the estimates calculated using national production data alumina production (top-down approach). In cases where a hybrid Tier 1 or Tier 3 approach is used during a transition period, it is considered *good practice* also to estimate emissions for all facilities using the lower Tier in order to compare the results of the analysis to the results derived using the hybrid approach. The results of such comparisons should be recorded for internal documentation, including explanations for any discrepancies.

REVIEW OF EMISSION FACTORS

Inventory compilers should compare aggregated national emission factors with the IPCC default factors in order to determine if the national factor is reasonable relative to the IPCC default. Differences between national factors and default factors should be explained and documented, particularly if they are representative of different circumstances.

If the aggregated top-down approach is used, but some limited plant-specific data are available, inventory compilers should compare the site or plant level factors with the aggregated factor used for the national estimate. This will provide an indication of the reasonableness and the representability of the data.

SITE-SPECIFIC ACTIVITY DATA CHECK

For site-specific data, inventory compilers should review inconsistencies between sites to establish whether they reflect errors, different measurement techniques, or result from real differences in emissions, operational conditions or technology. For alumina production, inventory compilers should compare plant data with other plants in the country.

Inventory compilers should ensure that emission factors and activity data are developed in accordance with internationally recognised and proven measurement methods. If the measurement practices fail this criterion, then the use of these emissions or activity data should be carefully evaluated, uncertainty estimates reconsidered, and qualifications documented. If there is a high standard of measurement and QA/QC in place at most sites, then the uncertainty of the emissions estimates may be revised downwards.

4.4.7.2 REPORTING AND DOCUMENTATION

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates. Specific documentation and reporting relevant to this source category follow.

TIER 1 METHOD

Any information regarding the carbonates content of sintering feed should be documented, including use of default values different from those discussed in section 4.4.5.3.

TIER 2 METHOD

Any county-specific information should be documented (technologies, amount of alumina produced by each technology type, amount and quality of lime used, etc.)

TIER 3 METHOD

When documenting the Tier 3 method it is important to document all the procedures undertaken and methodologies used to identify the weight fraction and identities of all carbonates, including carbonates incorporated in any raw materials along with the corresponding emission factors.

Estimating total emissions from carbonate inputs can overestimate emissions if the carbonates are not fully calcined. Any corrections should be documented. This includes documenting the fraction calcination of the raw materials and the quantity and fraction calcination of the SKD.

It is likely that plants will find it impractical to undertake chemical analyses of all raw material inputs on a daily basis for the purpose of CO_2 calculations. Instead, it is *good practice* for a full analysis to take place at each facility on a number of occasions throughout the year to fully characterise the carbonate inputs. Facilities will likely develop a relationship between carbonate input and alumina production that will be applied to the plant's routine calculation alumina production with sintering for intervening periods. In addition to identifying all procedures used to calculate emissions from the carbonate inputs, all steps necessary to identify the relationship between carbonate input and alumina production should be documented.

All underlying information should be documented and reported, it is not considered *good practice* to report just final emissions estimates.

4.5 MAGNESIUM PRODUCTION

No refinement.

4.6 LEAD PRODUCTION

No refinement.

4.7 ZINC PRODUCTION

No refinement.

4.8 RARE EARTHS PRODUCTION

This sub-chapter 4.8 “Rare Earths Production” provides new guidance for greenhouse gas (GHG) emissions from the primary production of rare earth (RE) metals and alloys[20], specifically CO_2 and perfluorocarbon (PFC) emissions. Since the *2006 IPCC Guidelines* do not have existing guidance on emissions from the rare earths industry, this is an entirely new sub-chapter, and follows on sub-chapter 4.7 Chapter 4 Volume 3 of the *2006 IPCC Guidelines*.

4.8.1 Introduction

‘Rare earths’ is used to refer to the group of 17 chemically similar metallic elements of scandium (Sc), yttrium (Y) and the lanthanides, i.e.: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu). The raw materials and trading goods are often in the form of rare earth oxides (REO).

Worldwide, primary production of many RE metals and alloys is carried out using a molten fluoride-salt electrolytic reduction process that is similar to primary aluminium’s Hall-Heroult process[21] (refer to sub-chapter 4.4). According to (Vogel & Friedrich 2015; Vogel & Friedrich 2018; Zhang *et al.* 2018), this involves:

- Dissolving and electrolytically reducing REOs (e.g. Nd_2O_3) in a molten salt of rare earth fluorides (REF_3) and lithium fluoride (LiF) – an example composition is 85 percent wt NdF_3, 10 percent LiF and 5 percent Nd_2O_3 for Nd metal production;
- Carbon anodes (e.g. graphite), which are consumed in the process;
- Cathodes, which are either inert (e.g. tungsten cathodes for Nd metal production) or are consumed in the process (e.g. Fe cathodes for Dy-Fe alloy production);
- A process that is carried out at high temperature (~1050-1100°C);
- Depending on the technology, a process that may be periodically interrupted or disturbed by anode replacements, cathode removal/replacement and removal of liquid RE metal/alloy, etc.

Nd is one of the most commonly produced RE metals by this process. Other RE metals and alloys produced via this route include: Pr, Pr-Nd, La, Dy-Fe, Gd-Fe, Ho-Fe, Ce, La-Ce, Y-Mg and mischmetal (Vogel & Friedrich 2018).

Alternative routes for RE metal and alloy production are outside the scope of these guidelines, since they are either not employed on an industrial scale or do not generate GHGs (Vogel & Friedrich 2018). These include chloride-salt electrolytic reduction (now largely replaced by the fluoride-based process) and calciothermic reduction (e.g. for production of samarium for Sm-Co magnets).

Industrial fluoride-based rare earth smelters vary in terms of electrical current (and hence size), the number and configuration of anodes and cathodes, and the level of automation in the process. Currently, the most widely used technologies are those at lower amperage (~5-6 kA) – these typically employ small round-shaped cells, with only single (or several) vertical anodes and cathodes and typically have very low levels of automation. Higher amperage technologies typically are larger, oval or rectangular shaped cells and are equipped with multiple vertical anodes and/or cathodes (Wen *et al.* 2004; Wen *et al.* 2012; Vogel & Friedrich 2015).

In general, the level of automation in rare earth production is considerably lower than that found in primary aluminium production (sub-section 4.4). However, some newer production technologies may be equipped with automatic process control features, including automatic feeding of REOs and automatic detection of anode effects, in order to increase production efficiency and reduce perfluorocarbon GHG emissions (refer to section 4.8.2.3).

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[20] CO_2 emissions associated with the production of electricity from fossil fuel combustion to produce rare earth metals and alloys are covered in Volume 2: Energy.

[21] Due to similarities between the primary aluminium and rare earth metal smelting processes (both produce metal from electrolysis of metal oxides in molten fluoride-salts, using consumable carbon anodes), the guidelines here for the rare earths industry have been adapted using existing guidelines for primary aluminium production (*2006 IPCC Guidelines*, Volume 3, Chapter 4, sub-chapter 4.4) as a basis. Although both processes generate CO_2 and PFC emissions through similar fundamental mechanisms, there are clear differences in technology and cell design, production scale, cathode and raw materials, operating conditions (amperage, voltage, temperature) and particularly levels of automation. Therefore, the guidance provided here is specific to current understanding of rare earth metals production.

In the fluoride-based rare earths smelting process, the most significant GHG process emissions are (Liu *et al.* 2001; Vogel *et al.* 2017; Cai *et al.* 2018):

1. CO_2 emissions from the consumption of carbon anodes in the electrolytic reaction converting rare earth oxides to rare earth metals;
2. PFCs emissions of CF_4 and C_2F_6 during anode effects. While not commonly observed, very low levels of C_3F_8 and trace levels of other PFCs (e.g. c-C_4F_8 and C_4F_{10}) have also been reported (Cai *et al.* 2018).

CO is another major process emission; SO_2 might also be emitted in very small amounts.

The decision trees in Figure 4.17 and Figure 4.18 provide guidance for selecting a methodology to estimate CO_2 and PFC emissions, respectively, from rare earth metal production. Since default emission factors have been provided, all inventory compilers in countries with rare earth metal production should be able to implement at a minimum level the Tier 1 method and thereby ensure completeness of reporting.

4.8.2 Methodological Issues

4.8.2.1 CHOICE OF METHOD FOR CO2 EMISSIONS FROM PRIMARY RARE EARTH METAL PRODUCTION

During normal operations, rare earth metals are produced at the cathode and carbon is consumed at the anode, forming CO and CO_2 gases by electrolysis, as per the generic electrolytic reduction reactions below for production of any RE from REO (Liu *et al.* 2001; Vogel *et al.* 2017) :

$$RE_xO_y + yC \rightarrow xRE + yCO$$

$$RE_xO_y + \frac{y}{2}C \rightarrow xRE + \frac{y}{2}CO_2$$

An example reaction for Nd metal production from its oxide is as follows:

$$Nd_2O_3 + 3C \rightarrow 2Nd + 3CO$$

$$Nd_2O_3 + 3/2\,C \rightarrow 2\,Nd + 3/2\,CO_2$$

For rare earth alloys that are formed by alloying with a consumable iron cathode during production, an example is the production of Dy-Fe alloy from its rare earth oxide; the reaction is as follows (Martinez *et al.* 2018):

$$Dy_2O_3 + 2x\,Fe \rightarrow 2Dy - Fe_x + 3\,CO$$

$$Dy_2O_3 + 2x\,Fe \rightarrow 2Dy - Fe_x + 3/2\,CO_2$$

While CO is the most dominant gas produced in these reactions (Liu *et al.* 2001; Vogel *et al.* 2017), it is assumed that all CO gas oxidises in the process and is ultimately emitted to the atmosphere as CO_2 gas (Vogel & Friedrich 2018), as follows:

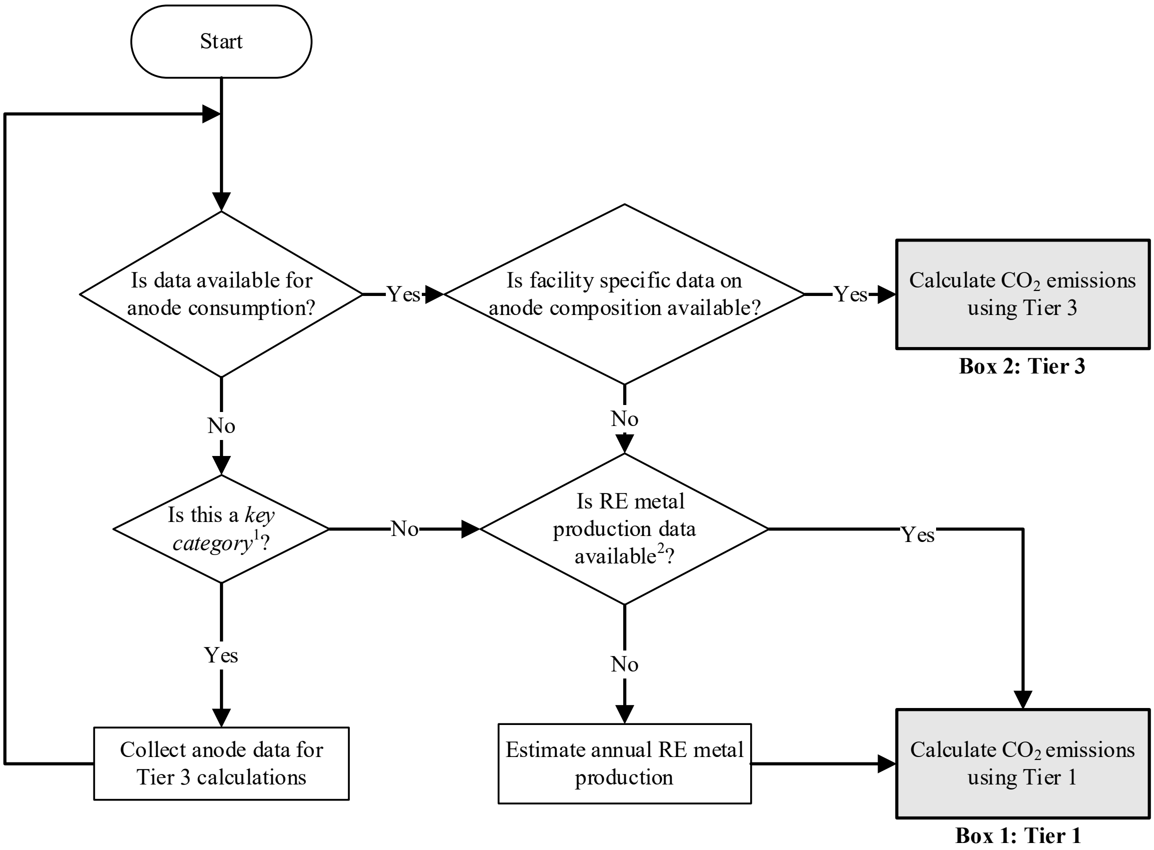
$$2CO + O_2 \rightarrow 2CO_2$$

Most CO_2 emissions therefore result from the electrolysis reaction of the carbon anode with rare earth oxides (REO). The consumption of carbon anodes is the principal source of process related CO_2 emissions from primary rare earth production. The reactions leading to CO_2 emissions are relatively well understood and the emissions are directly connected to the tonnes of RE metal or alloy produced, through the fundamental electrochemical equations for RE oxide reduction at a carbon anode and oxidation from thermal processes. Both of these fundamental processes producing carbon dioxide should be included in process parameters routinely monitored at production facilities, i.e. the net anode carbon consumed.

Due to a lack of published information, no other sources of process-related CO_2 emissions have been considered in these guidelines. For example, it is assumed that industrial rare earth facilities currently do not manufacture or 'pre-bake' their own carbon anodes, but rather they purchase graphite anodes. This is the case in the Chinese rare earth metal industry in 2018 (expert opinion), given the much lower process volumes and smaller anode sizes compared to the primary aluminium industry (which uses prebaked carbon anodes, refer to sub-chapter 4.4.2.1). Hence GHGs from anode baking (and associated energy use) are not considered here.

The decision tree shown in Figure 4.17 describes *good practice* in choosing the CO_2 inventory methodology appropriate for national circumstances.

Figure 4.17 (New) Decision tree for calculation of CO_2 emissions from primary rare earth (RE) metal production



Notes:

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

2. For Tier 1 CO_2 emissions calculation, the production data does not require differentiation of specific rare earth metals and alloys produced (Nd, Pr, Ce, La metals and/or Nd-Pr, Dy-Fe alloys, etc). There is also no need for further differentiation as to the type of rare earth cell technology used at each facility.

3. The decision tree only provides a two-tiered methodology: Tier 1 using default emission factors, and Tier 3 using facility-specific anode consumption + anode composition data. An additional Tier 2 method using default factors for anode composition data (corresponding to Tier 2 in the CO_2 decision tree for aluminium production, sub-chapter 4.4.2.1) has not been provided, since there is no default anode composition data for rare earths publicly available.

Tier 1 method for CO_2 emissions – default emission factors

The Tier 1 method for calculating CO_2 emissions is through multiplying a default emission factor by rare earth metal production. Given the uncertainty associated with the Tier 1 method, it is *good practice* to use higher tier methods if CO_2 from primary rare earths is a *key category*. Total CO_2 emissions from all rare earth (RE) metals and alloys produced are calculated according to Equation 4.35.

EQUATION 4.35 (NEW)
PROCESS CO_2 EMISSIONS FROM ANODE CONSUMPTION (TIER 1)

$$E_{CO_2} = \sum_i \left[EF_{CO_2} \bullet \left(AW_{base} / AW_i \right) \bullet MP_i \right]$$

Where:

E_{CO2} = Total CO_2 emissions from carbon anode consumption, tonnes CO_2

EF_{CO2} = CO_2 default emission factor for RE metal/alloys, tonnes CO_2/tonne RE metal

AW_{base} = Atomic weight of base case rare earth metal, i.e. neodymium = 144.24 g/mol

AW_i = Atomic weight of rare earth metal/alloy type *i*, g/mol

MP_i = Total metal production for RE metal/alloy type *i*, tonnes RE metal

Only one default CO_2 emission factor has been provided in these guidelines, taking Nd metal as the base case – refer to Table 4.26. The scarcity of published data means that default emission factors are not available for other RE metals and alloys. However, Equation 4.35 includes a factor to correct the default to account for differences in atomic weight among the RE metals. This factor is the atomic weight for Nd divided by the atomic weight of the metal or alloy actually produced. Taking Dy-Fe alloy as an example (assuming 80 percent Dy, 20 percent Fe by weight)[22], the atomic weight is 117.59 g/mol and the atomic weight ratio (AW_{base} / AW_i) is 1.23. Note that Equation 4.35 could be used for more precise estimates of total CO_2 emissions from RE metals production if more Tier 1 default factors for specific RE metals/alloys become available in the future. In that case, where an emission factor for a particular RE metal was applied to that RE metal, the atomic weight ratio (AW_{base} / AW_i) would simply be set to 1.

Tier 3 method for CO_2 emissions – by facility-specific carbon mass balance

In the Tier 3 method, CO_2 emissions are calculated using a mass balance approach that assumes that the carbon content of net anode consumption[23] is all ultimately emitted to the atmosphere as CO_2 gas[24]. The Tier 3 method uses actual concentrations of anode impurities from each facility. The choice of method between the Tier 1 and Tier 3 method will depend on whether process data for (i) net carbon anode consumption and (ii) baked anode composition are both available from individual facilities. Unfortunately, a more generic Tier 2 method (similar to that for aluminium production, in sub-section 4.4.2.1) using default factors for net anode consumption and anode composition (including impurity levels) is not available due to the scarcity of published information.

CO_2 emissions for the Tier 3 method are calculated according to Equation 4.36. This requires facility-specific operating data for all the components in Equation 4.36. Note this assumes the same anode composition is used for production of all RE metals and alloys; where the anode composition differs, replace Imp_a with Imp_i, the impurity content of the anodes used to produce each type of RE metal / alloy.

EQUATION 4.36 (NEW)
PROCESS CO_2 EMISSIONS FROM ANODE CONSUMPTION (TIER 3)

$$E_{CO_2} = \sum_i (NAC_i \bullet MP_i) \bullet [(100 - Imp_a)/100] \bullet (44/12)$$

Where:

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[22] Taking 100g basis for a Dy-Fe alloy with 80:20 wt fraction of Dy to Fe, the molar composition is 0.492 mol Dy, 0.358 mol Fe, or 58% mol Dy, 42% mol Fe. The atomic weight is therefore = 100 g / (0.492 + 0.358) mol = 117.59 g/mol.

[23] 'Net anode consumption' (NAC) refers to the total anode consumption per tonne of metal, minus any unused or 'spent' anode material when old anodes are exchanged for new anodes. This unused or 'spent' anode material is not consumed in the electrolysis process but might be recycled to make new anodes.

[24] While CO is the most dominant gas product from the rare earths electrolytic reduction reaction (Liu *et al.* 2001), it is assumed that any CO formed eventually is converted to CO_2 gas. The same carbon mass-balance approach is assumed for the primary aluminium industry, in sub-chapter 4.4.2.1.

E_{CO2} = Total CO_2 emissions from carbon anode consumption, tonnes CO_2

NAC_i = Net anode consumption per tonne of RE metal/alloy type *i*, tonnes anode/tonne RE metal

MP_i = Total metal production for RE metal/alloy type *i*, tonnes RE metal

Imp_a = Total content of non-carbon impurities (e.g. sulphur, ash, etc) in baked carbon anodes, wt %

44/12 = CO_2 molecular mass: carbon atomic mass ratio, dimensionless

Equation 4.36 can be applied to each rare earth smelter in the country and the results summed to arrive at total national emissions.

It is possible to use a hybrid Tier 1 and 3 approach if facility specific net anode consumption and composition data (impurity content, e.g. ash, sulphur, etc) are not available for each smelter.

4.8.2.2 CHOICE OF EMISSION FACTORS FOR CO_2 EMISSIONS FROM PRIMARY RARE EARTH METAL PRODUCTION

Tier 1 method for CO_2 emissions

Table 4.26 lists the default emission factors for CO_2 per tonne of RE metal, for use in Equation 4.35. Given the scarcity of published data and since only minor differences in emission factors are expected across different RE metals and alloy types[25], only one default emission factor is provided for all RE metals. This uses Nd metal production as the basis, since it is the most common RE metal produced via fluoride-salt electrolysis. It is *good practice* to check the EFDB as a source for future CO_2 emission factors for rare earth metals production.

TABLE 4.26 (NEW)
TIER 1 DEFAULT EMISSION FACTORS FOR CALCULATING CO_2 EMISSIONS FROM ANODE CONSUMPTION

Rare Earth Metal / Alloy ***i***	**Emission Factor, EF_{CO2} (tonnes CO_2/tonne RE metal)**	**Uncertainty Range (%)**
Nd metal, and all other Rare Earth metals/alloys	0.56 ^{a,b}	-22/+24% ^{c}

Source:

[a] CO_2 default emission factor is based on a net anode carbon consumption of 152 kg C/tonne RE metal (average anode consumption reported from 4 industrial production lines in China - (Cai *et al.* 2018)) and converting this to CO_2 by mass balance, assuming 100% conversion of anode carbon to CO_2, an approach consistent with that used in aluminium production (refer to section 4.4.2.1). These production lines are considered representative of current technology in China, where >90% of global RE metal was produced in 2018 (Cai *et al.* 2018); as such the default emission factor is considered representative of current global RE metal production, via fluoride-salt electrolysis. The emission factor is also consistent with values from a first principles / mass balance approach (see note b).

[b] A first principles calculation for CO_2 was done by taking electrolysis of Nd_2O_3 to Nd metal as a basis (see Section 4.8.2.1 for stoichiometric reactions), assuming a gas production ratio of ~75% CO, 25% CO_2 by direct electrolysis at 1050°C and anode current density of 1.0 A/cm^2 (Liu *et al.* 2001); Vogel and Friedrich (2015). CO_2 is then calculated assuming: (i) all CO is ultimately oxidised to CO_2, (ii) process has a 75% faradaic current efficiency (% anode carbon electrolytically consumed to produce metal), and (iii) an additional 10% anode carbon consumed via non-electrolytic processes (oxidation of carbon due to exposure with air). The obtained net anode carbon consumption (150 kg C / tonne RE metal) is consistent with that used for the default CO_2 emission factor.

TABLE 4.26 (NEW) (CONTINUED)
TIER 1 DEFAULT EMISSION FACTORS FOR CALCULATING CO_2 EMISSIONS FROM ANODE CONSUMPTION

[c] Assuming the default CO_2 emissions factor represents a current efficiency of 75%, an uncertainty range of -22%/+24% from the default CO_2 factor might be expected if individual facilities operate at a different current efficiency level (e.g. 60 to 95%), based on first principle calculations described in note b. However, actual variations in CO_2 emissions may be as low as ±10%, based on highest and lowest industrial net carbon anode consumption values reported in (Cai *et al.* 2018), converted by mass balance to CO_2. Therefore, where possible, development and use of Tier 3 emission factors is encouraged.

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[25] A difference of only -4% / +8% in CO_2 emission factors was estimated across different rare earth metals (from La to Gd metal, using Nd metal as a base case), when evaluating CO_2 emissions by first principles (refer to note 'b' in Table 4.26). This is due to due to the similarities in atomic mass for these rare earth metals.

Tier 3 method for CO_2 emissions

Table 4.27 lists the facility-specific activity data (and uncertainties) at individual facilities, for use in Equation 4.36. The most significant factors in Equation 4.36 are metal production and net anode consumption for each RE metal or alloy type i. Both these parameters should be collected from individual operating facilities for use with Tier 3. The other compositional terms in the equation make minor adjustments for non-carbon components of the anodes (e.g. sulphur and ash, expected to be <3 percent wt) and thus are not as critical. Tier 3 is based on the use of specific operating facility data for these minor components. Carbon consumed per tonne of metal produced is typically recorded by rare earth production facilities given its economic significance; facilities refer to this as 'net anode consumption' or 'net carbon consumption'.

TABLE 4.27 (NEW)
DATA SOURCES AND UNCERTAINTIES FOR PARAMETERS USED IN TIER 3 METHOD FOR CO_2 EMISSIONS FROM ANODE CONSUMPTION

Parameter	Data Source	Uncertainty (±%)
MP_i: total metal production for RE metal type *i* (tonnes metal per year)	Individual facility records	±10% [a]
NAC_i: net anode consumption per tonne of RE metal type *i* (tonnes per tonne metal)	Individual facility records	±10% [b]
Imp_a: total non-carbon impurity content in baked anodes (wt %) [c]	Individual facility records	±10% [b]

Source:

[a] Uncertainties in facility specific metal production records are expected to be low (i.e. ±10%, based on expert judgement). However note (Vogel & Friedrich 2018) estimates an uncertainty of up to ±40% (±15,000 tonnes) for the 35,000 tonnes estimated global RE metal production by fluoride electrolysis in 2015, due to unreported / illegal production of RE metals (Kingsnorth 2015).

[b] Uncertainties for CO_2 based on facility specific information (apart from metal production) have been estimated based on expert judgement, using uncertainty factors similar to those applied in the primary aluminium sector (sub-chapter 4.4, Table 4.11: uncertainties for Tier 3 method for CO_2 emissions from prebake cells).

[c] Non-carbon impurities can include sulphur, ash, etc.

4.8.2.3 CHOICE OF METHOD FOR PFCS

During electrolysis of a RE metal, rare earth oxides (REOs) are dissolved in a fluoride melt comprising of rare earth fluorides (RE_xF_y) and lithium fluoride (LiF). An example melt composition for Nd metal production is 85 percent wt NdF_3, 10 percent LiF and 5 percent Nd_2O_3.

Perfluorocarbons (mainly CF_4 and C_2F_6 – collectively referred to as PFCs) are formed from the reaction of the carbon anode with the fluoride melt (e.g. NdF_3 or DyF_3) during a process upset condition known as an 'anode effect'. This occurs when the concentration of dissolved REO in the electrolyte is too low to completely support the standard anode reaction (normally producing RE metal and CO/CO_2 gases), enabling additional anode reactions that form PFC gases (Vogel *et al.* 2017; Cai *et al.* 2018; Kjos *et al.* 2018; Zhang *et al.* 2018). In addition to CF_4 and C_2F_6, other PFCs reported by Cai *et al.* (2018) during RE metal production included: very low levels of C_3F_8 (<1 percent total PFCs) and trace levels of c-C_4F_8 and C_4F_{10} (<0.05 percent total PFCs). However, quantification of these PFCs (other than CF_4 and C_2F_6) in industrial measurements is extremely challenging and often impractical, given the extremely low detection limits required.

BOX 4.4 (NEW)

ANODE EFFECT DESCRIPTION (FOR RARE EARTH METAL PRODUCTION BY FLUORIDE ELECTROLYSIS)

An 'anode effect' is a process upset condition where an insufficient amount of rare earth oxide is dissolved in the electrolyte, resulting in the emission of PFC-containing gases and causing voltage to be elevated above normal operating range. However, PFC generation might also occur in the absence of detectable changes in voltage (Vogel *et al.* 2017; Kjos *et al.* 2018).

Unlike the analogous primary aluminium industry (refer to Box 4.2), many rare earth technologies currently do not use automated computer control systems to detect anode effects, for example using an elevated voltage threshold. As such, facility-specific activity data (e.g. anode effect performance data) is often not available to estimate PFC emissions.

Due to reported differences in emissions profile (Cai *et al.* 2018; Zhang *et al.* 2018), PFC emissions can be estimated separately for two groups of rare earth metals and alloys:

- *Rare earth-iron (RE-Fe) alloys*[26] with high melting-point (>1300°C) rare earth elements, e.g. Dy-Fe, Gd-Fe and Ho-Fe;
- *All other rare earth (Other-RE) metals/alloys* including single and mixed rare earth metals, e.g. Nd, La, Pr-Nd, etc.

In choosing a method for PFC emissions, it should be noted that the uncertainty associated with the Tier 3 methodology is significantly lower than for Tier 1; therefore it is *good practice* to use Tier 3 methodologies if this is a *key category*. However, a pre-requisite for the Tier 3 method is the availability of facility-specific emission factors, obtained through individual facility measurements. While no good practice guidance currently exists on the measurement of PFCs and obtaining Tier 3 emission factors for the rare earth industry, the US EPA and IAI protocols for measurement of PFCs in the aluminium smelting industry provide good analogous references (International Aluminium Institute 2006; US Environmental Protection Agency & International Aluminium Institute 2008).

The decision tree in Figure 4.18 describes *good practice* in choosing the PFC inventory methodology appropriate for national circumstances. The Tier 3 approach is preferred because plant-specific emission factors will lead to estimates that are more accurate. If no PFC measurements have been made to establish Tier 3 plant-specific emission factors, the Tier 1 method can be used until measurements have been made. Countries can use a combination of Tier 1 and Tier 3 depending on whether plant-specific emission factors are available from individual facilities.

Note that while the fundamental mechanisms that generate PFCs and anode effects in the rare earths industry are similar to those in primary aluminium production (refer to sub-chapter 4.4), the lack of automation currently found in the rare earths industry prevents the use of facility-specific activity data (e.g. using anode effect performance data as per Tier 2 and 3 methods for PFC accounting in primary aluminium production) as a more accurate methodology for estimating PFCs. Therefore, higher Tier 2 and 3 methods using process performance statistics or activity data have not been included in these guidelines[27].

While rare earths production currently has a lower level of automation and process control compared to primary aluminium production (see sub-chapter 4.4), the industry is still very much under development. There is ongoing research to develop industrial technologies that can minimise PFC emissions (e.g. employing automation to ensure control of REO concentrations) (Vogel & Friedrich 2017; Martinez *et al.* 2018). However, due to the scarcity of published information on industrial emissions, separate PFC emission factors have not been provided for these technologies.

Given the potential for further development within the industry, it is *good practice* to establish Tier 3 plant-specific emission factors for individual facilities where significant technology development and/or adoption of automated

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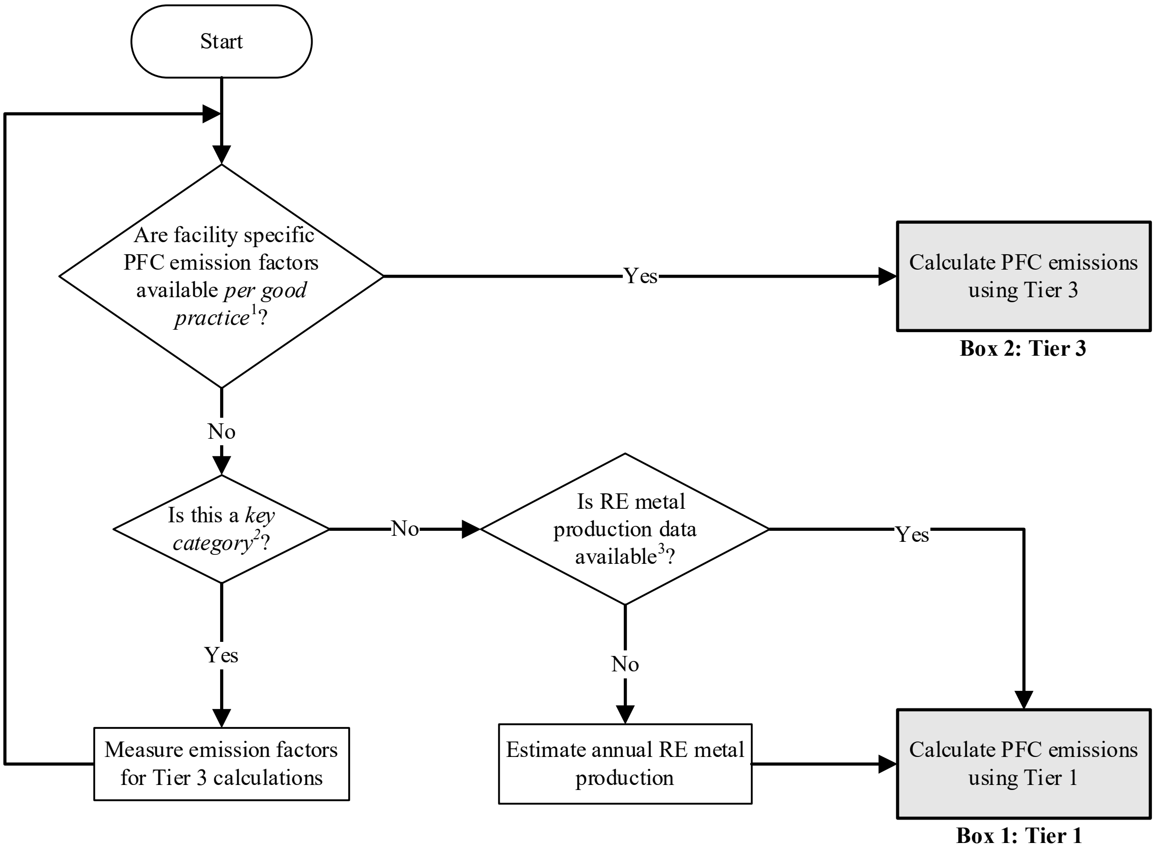
[26] This category of RE-Fe alloys represented <5% of total rare earth metals/alloys produced by electrolysis in 2016 (expert opinion). Due to their high melting point, these RE elements are typically produced using an alloying cathode (e.g. Fe) to form a liquid metal product, at higher operating cell voltage (compared to cells for all other RE metals/alloys in similar conditions). The higher operating temperature and cell voltage increases the risk of PFC generation and is thought to be one of the reasons behind the greater PFC emissions measured (expert opinion; Cai *et al.* 2018; Zhang *et al.* 2018).

[27] Accounting of PFCs using activity data - such as anode effect performance statistics - in the rare earths industry is possible. However this requires the industry to first have consistent definitions of anode effect performance, i.e. how to define the start/end of an anode effect to determine the frequency and the duration of anode effects. Secondly, the level of automation in rare earth facilities must be sufficiently high to ensure accurate and consistent records these anode effect performance statistics, a condition that does not currently reflect the majority of the rare earths industry.

control systems have taken place. Finally, it is *good practice* to check the EFDB as a source for future PFC emission factors for rare earths production.

Figure 4.18 (New) Decision tree for calculation of PFC emissions from primary rare earth (RE) metal production



Notes:

1. While *good practice* guidelines for obtaining facility specific PFC emission factors from rare earth production facilities are currently not available, the IAI and US EPA/IAI greenhouse gas protocols for aluminium smelters are useful references due to the many similarities between primary aluminium and rare earth smelting using fluoride-salts (International Aluminium Institute 2006; US Environmental Protection Agency & International Aluminium Institute 2008).

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

3. For Tier 1 PFC emissions calculation, the production data requires differentiation of (a) *rare-earth iron (RE-Fe) alloys*, e.g. Dy-Fe and (b) *all other rare earth (Other-RE) metals/alloys*, e.g. Nd, Pr-Nd and La. However, there is no need for further differentiation as to the specific rare earth metal/alloy produced, or type of rare earth cell technology used at each facility.

4. This decision tree only provides a two-tiered methodology: Tier 1 using default emission factors, Tier 3 using facility-specific emission factors. Additional Tier 2-3 methods using anode effect activity data to estimate PFC emissions (similar to the Tier 2-3 methods in the PFC decision tree for aluminium production, sub-chapter 4.4.2.3) has not been provided, due to the lack of available activity data.

Tier 1 and Tier 3 method for PFCs – by production

Both Tier 1 and Tier 3 methods for calculating PFCs employ emission factors that are based on metal production. Methods are provided for CF_4 and C_2F_6 gases since these are the major PFCs generated. C_3F_8 is also included for sake of completeness, however it is a very minor component of PFCs generated in rare earths (<1 percent total PFCs) and it can be challenging or impractical to quantify from industrial facilities (if obtaining Tier 3 facility-specific emission factors), given the extremely low detection limits required. Estimation of all other PFCs are beyond the scope of this method as they are not significant (Cai *et al.* 2018).

The Tier 1 method uses default emission factors based on industrial measurements. PFC emissions can be calculated according to Equation 4.37, where emission factors for CF_4, C_2F_6 and C_3F_8 gases are default emission factors (refer to Table 4.28). The level of uncertainty in the Tier 1 methodology is greater because individual facility emissions performance[28] is not taken into account. Note that some researchers (Vogel & Friedrich 2018) have estimated PFC emission factors two to three-orders of magnitude greater than the default values given in Table 4.28. These higher values were not used here because they were not measured, but modelled based on a mass balance of NdF_3 inputs to replace consumed fluorides, with the unlikely assumption that all consumed fluorides are due to PFC generation. Nevertheless, they do indicate that the PFC emission factors from some facilities may be higher than the Tier 1 factors presented here. Therefore, where possible, development and use of Tier 3 facility-specific PFC emission factors is encouraged.

Note that Equation 4.37 enables calculation of PFC emissions by individual RE metal/alloy produced. However default emission factors are only available for two generic types of metals/alloys: (i) *rare earth-iron alloys* (e.g. Dy-Fe) and (ii) *all other rare earth metals/alloys* (e.g. Nd, Pr-Nd), rather than all possible combinations of RE metals / alloys due to the scarcity of published industrial emissions data[29]. RE-Fe alloys were reported to have greater PFC emissions than other RE metals (Cai *et al.* 2018; Zhang *et al.* 2018), consistent with the greater risk of PFC generation expected with the higher temperature and cell voltage operation required. Therefore, two default Tier 1 emission factors for RE metals have been provided in these guidelines (Table 4.28). Hence, Equation 4.37 can be used with differentiation of RE metal production into these two metal/alloy types; further differentiation into specific RE metals/alloys is not required.

EQUATION 4.37 (NEW)
PFC EMISSIONS FROM RARE EARTH METALS PRODUCTION (TIER 1 AND TIER 3)

$$E_{CF_4} = \sum_i [(EF_{CF_4,i} / 1000) \bullet MP_i]$$

and

$$E_{C_2F_6} = \sum_i [(EF_{C_2F_6,i} / 1000) \bullet MP_i]$$

and

$$E_{C_3F_8} = \sum_i [(EF_{C_3F_8,i} / 1000) \bullet MP_i]$$

Where:

E_{CF4} = Emissions of CF_4 from RE metal production, kg CF_4

E_{C2F6} = Emissions of C_2F_6 from RE metal production, kg C_2F_6

E_{C3F8} = Emissions of C_3F_8 from RE metal production, kg C_3F_8

$EF_{CF4,i}$ = Emission factor by RE metal *i* for CF_4, g CF_4/tonne RE metal

$EF_{C2F6,i}$ = Emission factor by RE metal *i* for C_2F_6, g C_2F_6/tonne RE metal

$EF_{C3F8,i}$ = Emission factor by RE metal *i* for C_3F_8, g C_3F_8/tonne RE metal

MP_i = Metal production by RE metal *i*, tonnes RE metal

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[28] PFC emissions performance is impacted by technology, operating conditions and the anode effect performance of individual facilities. While anode effect performance data from facilities are used to directly estimate PFCs in the analogous aluminium smelting industry (refer to section 4.4.2.3), a similar method for rare earths has not been provided due to a lack of supporting data that characterises emissions according to process statistics, such as anode effect performance.

[29] While Tier 1 default emission factors are not available for all individual RE metal/alloy types, Equation 4.37 provides a template for the future (when such factors might become available) and for potential use in Tier 3 calculations.

The Tier 3 method uses facility-specific emission factors in place of Tier 1 default emission factors. Facility-specific emission factors are calculated from direct PFC measurement data at the individual facility (either continuous or periodic measurements) and are obtained using established measurement practices and protocols – refer to analogues guidelines for the aluminium industry (International Aluminium Institute 2006; US Environmental Protection Agency & International Aluminium Institute 2008)). It is *good practice* to use the Tier 3 method to estimate PFCs from rare earths when that is a *key category*.

For Tier 3, if facility-specific emission factors and production data are available for individual RE metals and alloys, then Equation 4.37 can be employed to calculate differentiated PFC emissions for each RE metal/alloy; total PFC emissions can be obtained via the summation of these differentiated emissions. However, if differentiated emission factors and production data by RE metal/alloy are unavailable, it is acceptable to use Equation 4.37 without differentiation of RE metals/alloys produced.

Given the practical challenges in quantifying very low levels of C_3F_8, if a Tier-3 facility-specific emission factor cannot be determined, it is possible to use a hybrid Tier 1-Tier 3 approach (i.e. Tier 1 emission factor for C_3F_8; Tier 3 emission factors for CF_4 and C_2F_6).

4.8.2.4 CHOICE OF EMISSION FACTORS FOR PFCS

Tier 1: Default emission factors for PFCs

Default emission factors for the Tier 1 method of estimating PFC emissions from rare earth metal production are provided in Table 4.28, for use in Equation 4.37.

TABLE 4.28 (NEW)
TIER 1 DEFAULT EMISSION FACTORS AND UNCERTAINTY RANGES FOR THE CALCULATION OF PFC EMISSIONS FROM RARE EARTH PRODUCTION

	CF_4		C_2F_6		C_3F_8	
Rare Earth Metal, *i*	***EF*** EF_{CF4} **(g/tonne RE metal)**	**Uncertainty Range [c] (+/-%)**	EF_{C2F6} **(g/tonne RE metal)**	**Uncertainty Range [c] (+/-%)**	EF_{C3F8} **(g/tonne RE metal)**	**Uncertainty Range [c] (+/-%)**
RE-iron alloys (Dy-Fe, etc) [a]	146.1	+/- 99%	14.6	+/- 99%	0.05	+/- 99%
Other-RE metals/alloys (Nd, Pr-Nd, La, etc) [b]	35.8	-54% / +30%	5.2	-95% / +108%	0.21	-52% / +30%

Sources:

[a] For *rare earth-iron (RE-Fe) alloys*, CF_4 default emission factors is based on the average of industrial measurements from production of Dy-Fe alloy (1 cell, two measurements from the same facility) in China (Cai *et al.* 2018; Zhang *et al.* 2018). Note that the (Zhang *et al.* 2018) value of 106 g CF_4/tonne RE metal was corrected by dividing out the 57.97% gas collection efficiency measured at the facility by (Cai *et al.* 2018). C_2F_6 and C_3F_8 default emission factors were calculated using the CF_4 default factor, multiplied by the respective C_2F_6/CF_4 and C_3F_8/CF_4 ratio measured by (Cai *et al.* 2018) for Dy-Fe production. Given that default factors are based on only two data points, a higher uncertainty bound +/-99% has been estimated (expert opinion) rather than using the lowest/highest reported emission values.

[b] For *all other rare earth (Other-RE) metals/alloys*, CF_4 default emission factors is based on the average of industrial measurements from production of: (i) Nd metal (16 cells, one facility) (Zhang *et al.* 2018), with the value of 26.9 g CF_4/tonne metal corrected by dividing out the 57.97% gas collection efficiency measured at the facility by (Cai *et al.* 2018) and (ii) Pr-Nd alloy (15 cells, 6 cells in two facilities) and La metal (6 cells, one facility) in China (Cai *et al.* 2018). C_2F_6 and C_3F_8 default emission factors were calculated using the CF_4 default factor, multiplied by the average C_2F_6/CF_4 and C_3F_8/CF_4 ratio, respectively, measured by (Cai *et al.* 2018) from Pr-Nd alloy (15 cells, 6 cells) and La metal (6 cells) production. The uncertainty range is estimated from the lowest/highest emission values from both industrial studies.

[c] Note that the default factors and uncertainty ranges here have been estimated with very limited sources of measured industrial data. Some researchers (Vogel & Friedrich 2018) have estimated PFC emission factors two to three-orders of magnitude greater than the default values in this table (modelled 'medium-emissions' scenario for Nd production, based on mass balance of NdF_3 inputs to replace consumed fluorides, but with the unlikely assumption that all consumed fluorides are due to PFC generation). Therefore where possible, development and use of Tier 3 facility-specific PFC emission factors is encouraged.

Tier 3: Facility-specific emission factors for PFCs

The Tier 3 facility-specific emission factors (and uncertainties), determined through direct PFC measurements at individual facilities is listed in Table 4.29, for use in Equation 4.37.

TABLE 4.29 (NEW)
DATA SOURCES AND UNCERTAINTIES FOR PARAMETERS USED IN TIER 3 METHOD FOR PFC EMISSIONS

Parameter	**Data Source**	**Uncertainty (+/-%)**
EF_{CF4}: CF_4 emission factor for metal type i (kg CF_4/tonne RE metal)	Individual facility records	±10% [a]
EF_{C2F6}: C_2F_6 emission factor for metal type i (kg C_2F_6/tonne RE metal)	Individual facility records	±10% [a]
EF_{C3F8}: C_3F_8 emission factor for metal type i (kg C_3F_8/tonne RE metal)	Individual facility records	±35% [a]
MP_i: metal production for RE metal type i (tonnes metal per year)	Individual facility records	±10% [b]

Source:

[a] Uncertainties for facility-specific emission factors have been derived from estimated sampling and gas analysis uncertainties during direct industrial measurement of PFCs in rare earth facilities (Cai *et al.* 2018). Uncertainties for C_2F_6 and especially C_3F_8 can be higher, particularly when concentrations are close to detection limits of gas measurement systems. Determination of Tier 3 facility-specific emission factors for C_3F_8 can be challenging and impractical, given the very low detection limits required to quantify these low-level emissions. It is possible therefore to use a hybrid Tier 1-Tier 3, where C_3F_8 emissions are estimated using Tier 1 default factors, and CF_4 and C_2F_6 using Tier 3, respectively.

[b] Uncertainties in facility specific metal production records are expected to be low (i.e. ±10%, based on expert opinion). However (Vogel & Friedrich 2018) estimates an uncertainty of up to +40% (+15,000 tonnes) for the 35,000 tonnes estimated global RE metal production by fluoride electrolysis in 2015, due to unreported / illegal production of RE metals (Kingsnorth 2015).

4.8.2.5 CHOICE OF ACTIVITY DATA AND EMISSION FACTORS

Production statistics should be available from every facility to enable use of the Tier 1 methods for both CO_2 and PFC emissions. Therefore, uncertainty in the tonnes of rare earth metals and alloys produced is likely to be low in most countries that have good reporting systems (±10 percent uncertainty, based on expert judgement); other sources (Vogel & Friedrich 2018) estimate up to +40 percent uncertainty in global RE metal production (in 2015) due to the presence of unreported or illegal RE metal production in some parts of the world.

For PFC emissions, it is *good practice* to use Tier 3 facility-specific emission factors for individual facilities, where reliable measurements have been taken to establish facility-specific emission factors (i.e. using a method similar to that in the USEPA/IAI Protocol for Measurement of CF_4 and C_2F_6 emissions from Primary Aluminium Production, 2008).

For CO_2 emissions, it is also *good practice* to collect data to support Tier 3 methods, which requires facility specific information on anode consumption and anode composition to calculate CO_2 emissions.

4.8.2.6 COMPLETENESS

Completeness for this source category requires accounting for both CO_2 and PFC emissions during the production of rare earth metals. Primary RE metal production facilities (by fluoride-electrolysis of REOs) are expected to have the information required for these estimates, including records of the tonnes of RE metals produced (both total and by individual RE metal/alloy types) throughout the entire time series covered by the inventory. In addition, anode consumption data are expected to be available over the same period. Primary RE production (by fluoride-electrolysis of REOs) also utilizes a high intensity of electricity (per tonne of RE metal); however carbon dioxide emissions associated with electricity input are covered separately under Volume 2: Energy.

Completeness also requires that all rare earth metals production and/or all rare earth metal producers in the country be identified. As noted above, some sources have estimated that global RE metal production may have been underestimated by 40 percent in 2015 due to unreported or illegal RE metal production in some parts of the world (Vogel & Friedrich 2018).

4.8.2.7 DEVELOPING A CONSISTENT TIME SERIES

Rare earth metal/alloy production statistics should be available for the entire history of the facility.

Developing a consistent time series for CO_2 emissions should not be a problem since it is expected that most facilities have measured and recorded activity data for anode consumption and composition. Where historic anode consumption and compositional data are missing, carbon dioxide emissions can be estimated from RE metal production utilizing the Tier 1 method.

Developing a consistent time series for PFC emissions should also be reasonably straightforward as both Tier 1 and 3 methods utilise metal production statistics to estimate emissions. Backcasting of Tier 3 methods is preferred over the use of Tier 1 emission factors. Because PFC emissions have only recently become a focus area of the rare earths industry, the majority of facilities do not have further activity data to support any other methodologies (e.g. process-data on anode effect performance as per the primary aluminium industry, sub-chapter 4.4.2.3).

It is *good practice* to consult with representatives from the operating facilities, either directly or through regional, national or international organizations representing the rare earths industry to develop the best strategy for the specific group of operating locations included in the national inventory.

4.8.3 Uncertainty assessment

There are major differences in the uncertainty for PFC emissions depending on the choice of Tier 1 or Tier 3 methods. The differences in uncertainty resulting from the choice of Tier 1 or Tier 3 methods for CO_2 emissions is smaller, but still significant.

4.8.3.1 EMISSION FACTOR UNCERTAINTIES

Uncertainties in CO_2 emission factors

For CO_2 emissions, there are major differences in the uncertainty of emissions depending on the choice of Tier 1 or 3 methods. The overall uncertainty in calculating CO_2 emissions from carbon anode consumption for Tier 3 should be less than ±20 percent, and less than ±30 percent for Tier 1. While Tier 1 default emission factors are calculated using the same first principles as Tier 3 (mass-balance assuming all carbon content in the net anode consumed is emitted as CO_2), there are assumptions for Tier 1 which increases the level of uncertainty. These include: (i) an assumed net anode consumption and (ii) assuming zero non-carbon impurities, i.e. 100 percent of net anode consumed is in the form of carbon. The use of facility-specific net anode consumption and anode compositional data in the Tier 3 method removes the need for these assumptions, leading to lower uncertainty in calculating CO_2 using Tier 3. This is because the reactions leading to carbon dioxide emissions is reasonably well understood and the emissions are very directly connected to the tonnes of RE metal produced through fundamental electrochemical equations for REO reduction at the carbon anode and oxidation from thermal processes. Both these processes are taken into account when calculating CO_2 using net anode consumption and anode compositional data.

Uncertainties in PFC emission factors

For PFC emissions, there are major reductions in uncertainty when choosing the Tier 3 over the Tier 1 method. The high level of uncertainty in the Tier 1 method results from the default emission factors being based on only two sets of industrial PFC measurements from rare earth facilities (Cai *et al.* 2018; Zhang *et al.* 2018). Due to the limited number of industrial measurements, there is no differentiation of Tier 1 default emission factors for different rare earth metals and production technologies, apart from the two generic metal/alloy types: (i) rare earth-iron (RE-Fe) alloys and (ii) all other rare earth (Other-RE) metals/alloys. In order to achieve lower uncertainty using Tier 3 PFC calculations, it is important to use *good practices* in making facility specific PFC measurements. Measurement *good practices* have been established for the aluminium industry in a protocol available globally (International Aluminium Institute 2006; US Environmental Protection Agency & International Aluminium Institute 2008); due to the similarities between the industries, these are recommended as a guiding reference for measurements in the rare earths industry, until a RE industry-specific protocol or guideline is established. When properly obtained, the Tier 3 coefficients will have an uncertainty of ±10 percent for CF_4 and C_2F_6 and ±35 percent for C_3F_8 at the time coefficients are measured (Cai *et al.* 2018).

4.8.3.2 ACTIVITY DATA UNCERTAINTIES

While uncertainties in annual production data for RE metals should be minor (less than ±10 percent), there are some reports of unreported/illegal production in parts of the world that amount to ±40 percent of estimated global metal production in 2015 (Kingsnorth 2015; Vogel & Friedrich 2018). The uncertainty in recorded carbon anode consumption is estimated to be low (less than ±10 percent).

4.8.4 Quality Assurance/Quality Control (QA/QC), Reporting and Documentation

4.8.4.1 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

It is *good practice* at all primary rare earth metal production facilities to maintain records of all the necessary activity data to support calculations of emission factors as suggested in these guidelines. These records will include production of rare earth metals (ideally by RE metal/alloy type and by RE technology type) and consumption of carbon materials used. It is *good practice* to aggregate emission estimates from each smelter to estimate total national emissions. However, if smelter-level production data is unavailable, smelter capacity data may be used along with aggregate national production to estimate smelter production.

It is *good practice* to verify facility CO_2 emission factors per tonne of RE metal by comparison with the expected range of variation that would be predicted from the variation noted in Table 4.26 for CO_2 specific emissions. Similarly, facility-specific PFC emission factors per tonne RE metal should be compared with the expected range of variation noted in Table 4.28. It is suggested that any inventory value outside the expected range of variation be confirmed with the data source.

Use of standard measurement methods improves the consistency of the resulting data and knowledge of the statistical properties of the data. Until a rare earths industry-specific guideline or protocol has been established, the US EPA 'Protocol for Measurement of Tetrafluoromethane (CF_4) and Hexafluoroethane (C_2F_6) Emissions from Primary Aluminum Production' (US Environmental Protection Agency & International Aluminium Institute 2008) is an internationally recognized standard and can be used as a guidance document for obtaining PFC emission factors for a rare earths facility, given the similarities between aluminium and rare earths fluoride-electrolysis processes[30]. It is *good practice* to encourage plants to use this method for developing Tier 3 PFC emission factors. Significant differences between calculated coefficients based on PFC measurements and the industry average Tier 1 emission factors should elicit further review and checks on calculations. Large differences should be explained and documented.

Inter-annual changes in emissions of carbon dioxide per tonne RE metal are not likely to exceed ± 20 percent[31] based on the consistency of the underlying processes that produce carbon dioxide. In contrast, inter-annual changes in emissions of PFCs per tonne of RE metal may change by values as much as ±100 percent[32]. Increases in PFC specific emissions can result from process instability or major changes in process conditions, such as unforeseen power interruptions, changes in sources of REO feed materials, cell operational problems, and changes in amperage to increase RE metal production. Decreases in PFC specific emissions can result from upgrades in cell technology such as increasing automation, installation of equipment to continuously feed REO, improved work practices and better control of raw materials.

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[30] Note that unlike the aluminium industry, the Tier 3 methodology for rare earths estimates PFCs using production-based emission factors only. The method does not consider more detailed process data, such as anode effect coefficients and performance data (as per the Tier 2-3 methodology for accounting PFCs from aluminium in sub-chapter 4.4), due to a lack of published data to support it.

[31] Inter-annual variations in CO_2 emissions in the analogous aluminium industry (sub-chapter 4.4) typically do not vary more than ± 10%; however, given the scarcity of published data, greater variations (i.e. ± 20%) might be allowed for in the rare earth industry.

[32] Inter-annual variations in PFC emissions in the analogous aluminium industry (sub-chapter 4.4) typically do not vary more than ± 100%; a similar level of variations might be expected in the rare earth industry, as supported by reductions in measured emissions over time in one facility (Cai *et al.* 2018).

4.8.4.2 REPORTING AND DOCUMENTATION

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Volume 1, Chapter 6, Quality Assurance and Quality Control, Internal Documentation and Archiving. Some examples of specific documentation and reporting relevant to this source category are provided below.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced. To improve transparency, it is *good practice* to report emissions for PFCs from rare earths production separately from other source categories. Additionally, it is *good practice* that CF_4, C_2F_6 and C_3F_8 emissions are reported separately on a *mass basis*.

The supporting information necessary to ensure transparency in reported emissions estimates is shown in Table 4.30 below.

Much of the production and process data are considered proprietary by operators, especially where there is only one smelter in a country. It is *good practice* to exercise appropriate techniques, including aggregation of data, to ensure protection of confidential data.

TABLE 4.30 (NEW)
GOOD PRACTICE REPORTING INFORMATION FOR CALCULATING CO_2 AND PFC EMISSIONS FROM RARE EARTH METAL PRODUCTION BY TIER

Data	Tier 1	Tier 3
CO_2 emissions		
Annual national production (by metal and alloy type)	X	
Annual production by facility (by metal and alloy type)		X
Net anode consumption		X
Anode composition / impurity		X
PFC emissions (CF_4, C_2F_6 and C_3F_8 reported separately on mass basis)		
Annual national production (by metal/alloy type)	X	
Annual production by facility (by metal/alloy type)		X
Default technology emission coefficients	X	
Facility-specific emission coefficients		X
Supporting documentation	X	X

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CHAPTER 6

ELECTRONICS INDUSTRY EMISSIONS

Authors

Laurie Beu (USA) and Sebastien Raoux (France/USA)

Yun Chung (Jack) Chang (USA), Michael Roger Czerniak (UK), Francesca Illuzzi (Italy), Tetsuya Kitagawa (Japan), Deborah Ottinger (USA) and Natalya Parasyuk (Ukraine)

Contributing Authors

Stephanie N. Bogle (USA), Shoumian Chen (China), Joseph Van Gompel (USA), Melissa Ann Gresham (USA), David Harman (USA), Kyungah Kim (Republic of Korea), Joey (Ching-Hui) Lu (Taiwan, Province of China), Youngsook Lyu (Republic of Korea), Brian K. Raley (USA) and Jennifer Politsch (USA)

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6 ELECTRONICS INDUSTRY EMISSIONS

Users are expected to go to the Mapping Tables in Annex 5, before reading this chapter. This is required to correctly understand both the refinements made and how the elements in this chapter relate to the corresponding chapter in the 2006 IPCC Guidelines.

This Chapter 6 Volume 3 of the *2019 Refinement* is a complete update 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*.

The *2019 Refinement* of Volume 3 Chapter 6 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 2018 compared to 2006) to calculate default emissions factors for the sector. Also, several methodological refinements are introduced in an attempt to increase accuracy and flexibility, depending on how reporting facilities track gas usage and implement emissions control technologies. The *2019 Refinement* includes six revised methods (Tier 1, 2a, 2b, 2c, 3a, and 3b), compared to four for the *2006 IPCC Guidelines*. Section 6.1.2 and the mapping Tables in Annex 5 summarize the substantial refinements of this Chapter. Annex 5 provides a list of the sections, equations, tables, figures, and boxes that have been refined in this chapter, describing the type of refinement and a comparison between the *2006 IPCC Guidelines* and the *2019 Refinement*.

6.1 INTRODUCTION

6.1.1 Overview of emissions and their sources

As part of its manufacturing processes, the electronics industry uses and emits greenhouse gases (GHGs) from the family of fluorinated compounds (FCs) and nitrous oxide (N_2O). The specific electronic industry sub-sectors 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 diodes (OLEDs). FC emissions from waterproofing of electronic circuits are discussed in Chapter 8 of this Volume.

6.1.1.1 COMPOUNDS USED AND EMITTED

The electronics industry currently emits both FCs that are gases at room temperature (FC gases) and fluorinated compounds that are liquids at room temperature (fluorinated liquids) and that enter the atmosphere through evaporation. FC gases are used in two important steps of electronics manufacturing: (i) plasma etching and wafer cleaning (EWC) of silicon-containing materials and (ii) cleaning of the chamber walls of thin-film deposition (TFD) and diffusion tools after processing substrates. Electronic manufacturers also use fluorinated liquids as heat transfer fluids (HTFs) 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, fluorinated liquids are sometimes used to clean substrate surfaces, e.g., for MEMS. (Before 2010, fluorinated liquids were occasionally used to clean TFT-display panels during manufacture, but this is no longer believed to be the case.) Finally, electronics manufacturers use N_2O as an input gas during TFD processes and for other N_2O-using manufacturing processes such as diffusion and dry removal of photoresist.

For the purpose of this Chapter, FC gases are defined to include perfluoromethane (CF_4), perfluoroethane C_2F_6, perfluoropropane (C_3F_8), 1,3-hexafluorobutadiene (C_4F_6), perfluorocyclobutane (c-C_4F_8), octafluorotetrahydrofuran (C_4F_8O), octafluorocyclopentene (c-C_5F_8), trifluoromethane (CHF_3), difluoromethane (CH_2F_2), fluoromethane (CH_3F), pentafluoroethane (C_2HF_5), nitrogen trifluoride (NF_3), and sulphur hexafluoride (SF_6). Although not considered to be greenhouse gases, carbonyl fluoride (COF_2), and fluorine (F_2) should be tracked as input gases because they are known to create FC gas by-products which should be included in the inventory. Fluorinated liquid emissions consist primarily of hydrofluoroethers, perfluoropolyethers (including PFPMIE), and other fully fluorinated liquids (perfluorinated amines and perfluoroalkylmorpholines). More than 40 different fluorinated liquids are marketed to the electronics industry, often as mixtures of fully fluorinated compounds. Although this list of FC gases and classes of fluorinated liquids is believed to include all relevant compounds used in appreciable quantities for the production of electronic devices as of this writing, FC gases and fluorinated liquids that should be considered for inventory purposes under this Chapter could also include other fluorinated compounds currently used in small quantities for production or for research and development (R&D) purposes, and FC gases and fluorinated liquids that may be used in the future for manufacturing electronic devices. In general, fluorinated compounds that are greenhouse gases or whose use during the manufacturing of electronic devices could result in emissions of greenhouse gases should be considered.

6.1.1.2 PROCESSES LEADING TO EMISSIONS

Both plasma etching and wafer and thin film deposition chamber cleaning processes use plasma or thermal energy to break down fluorinated compounds into fluorine atoms and other reactive species to perform these process steps. TFD and other N_2O-using processes also use plasma or thermal energy to break down N_2O molecules and generate oxygen or nitrogen atoms or molecules and other excited species to perform the process. The majority of FC gases and N_2O emissions result from the failure to completely break down the FC gases or N_2O molecules that are fed into the process, causing the utilisation efficiency of the input gases to be limited. In this chapter, input gases are generally designated with the subscript "i." In addition, a fraction of FC input gases used in the production process can be converted into FC gas by-products such as CF_4, C_2F_6, C_4F_6, C_4F_8, C_3F_8, CHF_3, CH_2F_2, and CH_3F. Several of these by-products can also be formed even if no carbon-containing FCs are fed into the process. In particular, processes using molecular fluorine (F_2), nitrogen trifluoride (NF_3), sulphur hexafluoride (SF_6), or chlorine trifluoride (ClF_3) input gases can generate CF_4, C_2F_6, CHF_3, CH_2F_2, CH_3F (and potentially other FC gases) as by-products of etching carbon-containing materials or cleaning chambers previously used to deposit carbon-containing thin films.[1] Moreover, under certain circumstances, CF_4 may be formed in combustion-based emissions control systems using hydrocarbon fuels by reaction between the fuel and fluorinated species (e.g. F_2) emitted during F_2 and remote NF_3 chamber cleans; thus, an appropriate CF_4 by-product emission factor ($AB_{CF4,\ F2}$) should be used to account for this phenomenon. In this chapter, by-product gases are generally designated with the subscript "k" (or "k,i" where a particular input gas "i" reacts to form the by-product "k"). Finally, with respect to fluorinated liquids, emissions occur through evaporative losses. Table 6.1 summarizes the sources and types of GHGs emitted during electronics manufacturing and identifies the section of this Refinement where they are discussed.

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[1] When using cleaning or etching gases that do not contain carbon (e.g. F_2, NF_3, SF_6, or ClF_3), CF_4 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_4 and other FC by-products with high GWPs should be taken into account, even when the cleaning or etching precursor itself has no or low global warming potential (such as F_2, COF_2, or ClF_3). Please see section 6.2.2.1 for more detail.

Table 6.1 (New)
Sources and types of GHGs emitted during Electronics Manufacturing

Source	GHG(s) Emitted	Relevant Sections of Volume 3 of *2019 Refinement*
Incompletely utilized FC gases fed into plasma etching, wafer cleaning, and chamber cleaning processes	Multiple FC gases	6.2.1.1, 6.2.2.1
By-products formed from carbon-containing FC gases fed into plasma etching, wafer cleaning, and chamber cleaning processes	Multiple FC gases	6.2.1.1 (See especially Box 6.2), 6.2.2.1
By-products formed from fluorine-containing gases (e.g., NF_3, F_2, COF_2) fed into plasma etching, wafer, cleaning, and chamber cleaning processes that involve carbon-containing films	Multiple FC gases	6.2.1.1 (See especially Box 6.2 and discussion following Equation 6.6), 6.2.2.1
By-product formed in some combustion-based FC emissions control systems	CF_4	6.2.1.1 (Equation 6.7 for Tiers 2a and 2b, Equation 6.15 for Tiers 2c and 3a)
Incompletely utilized N_2O fed into thin film deposition and other (e.g., diffusion) processes	N_2O	6.2.1.1 (throughout)
Fluorinated liquids used for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering	Multiple FC liquids	6.2.1.2, 6.2.2.2, (See especially Table 6.5)
FCs emitted during waterproofing of electronic circuits	Multiple FC gases	Chapter 8, section 8.3 (See discussion near Equation 8.22A)

6.1.2 Summary of refinements

The Tier 1 method of the *2019 Refinement* uses the same approach as in the *2006 IPCC Guidelines*, where emissions are estimated based on the surface area of substrate produced for each sub-sector, but the Tier 1 default emissions factors (EFs) for semiconductor and display manufacturing have been updated to account for technological advancements and for the use of a broader basket of FC gases and fluorinated liquids. In addition, default EFs for MEMS have been introduced.

The Tier 2 and 3 methods of the *2019 Refinement*, like their predecessors in the *2006 IPCC Guidelines*, are based on gas consumption. The 2006 Tier 2a method is updated as a new refined 2019 Tier 2a method for the semiconductor sub-sector with revised emission factors, also accounting for additional precursors and by-products. For the display sub-sector, the *2019 Refinement* no longer provides a Tier 2a method because it is typically not needed. For the PV sub-sector, the 2006 Tier 2a method default factors cannot be applied to the 2019 Tier 2a method.

The 2006 Tier 2b method, which formerly distinguished emission factors by process type (etch versus chemical vapour deposition (CVD)[2] chamber clean) is now replaced with a new refined 2019 Tier 2b method using emission factors applicable to different wafer sizes for the semiconductor sub-sector (≤200 mm or 300 mm). Note that the revised 2019 Tier 2b method no longer distinguishes EFs by process type (this is now done under the new 2019 Tier 2c method), and that the 2019 Tier 2b method is applicable only to the semiconductor sub-sector.

The new 2019 Tier 2c method for the semiconductor sub-sector distinguishes emissions factors by both wafer size (≤200 mm or 300 mm), and by refined process type. For the display and PV sub-sectors, the Tier 2c method does not distinguish by substrate size but provides differentiated emission factors by process type.

Using the Tier 2 and Tier 3a methods requires some degree of apportioning of gas consumption. That is, the consumption of input gases should be differentiated by process type (e.g. etching vs. chamber cleaning). Compared to the *2006 IPCC Guidelines*, the *2019 Refinement* provides additional guidance to apportion gas consumption to different process types.

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[2] This chapter uses the term “thin-film deposition,” which encompasses chemical vapour deposition as well as other thin film deposition techniques.

The 2006 Tier 3 method, which was based on process-specific parameters, has evolved into a new 2019 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 sub-sectors (semiconductor, display, MEMS, PV).

The *2019 Refinement* includes a new 'stack' Tier 3b method to develop site-specific emission factors based on measurements at the stack level. Like the Tier 3a method, the 3b method is applicable to all sub-sectors.

Finally, it should be noted that, in addition to emissions arising from the direct manufacture of semiconductor, display, MEMS, and PV devices themselves, account has also been taken in the *2019 Refinement* for GHG emissions (including a variety of FC gases) from the application of thin, conformal waterproofing films to assembled circuit boards as used in electronic devices that are likely to be exposed to the weather; a good example being mobile ("cellular" or "smart") phones. This is discussed separately in Chapter 8 of the *2019 Refinement.*

Table 6.2 summarizes the refinements and applicability of each Tier by electronics industry sub-sector.

TABLE 6.2 (NEW)
REFINEMENTS AND APPLICABILITY OF GUIDANCE BY ELECTRONICS INDUSTRY SUBSECTOR

Electronics Industry Subsector	**Gaseous Fluorinated Compounds and N_2O**						**Fluorinated Liquids**	
	Tier 1	**Tier 2a**	**Tier 2b**	**Tier 2c**	**Tier 3a**	**Tier 3b**	**Tier 1**	**Tier 2**
Semiconductors	U	U	U	NG	U	NG	U	NR
Display (formerly "FPD" or "LCD")	U	*NA*	*NA*	U[1]	U	NG	U	NR
Photovoltaic	NR	*NA*	*NA*	U[2]	U	NG	U	NR
MEMS	NG	*NA*[3]	*NA*[3]	*NA*[3]	U	NG	U	NR

U – Update, NG – New Guidance, NR – No Refinement, *NA* – Not Applicable

[1] For display, the Tier 2c method now includes a default emission factor for N_2O TFD but is otherwise similar to the former 2b method. The Tier 2c method does not distinguish by substrate size for display.

[2] While the Tier 2 methods for all electronics sub-sectors were updated (e.g., to include additional guidance on gas apportioning and abatement), the default Tier 2c emission factors for photovoltaic manufacturing were not updated and are the same as for the *2006 IPCC Guidelines* Tier 2b method.

[3] Data were not available to calculate separate Tier 2 default EFs for MEMS manufacturing, but the corresponding Tier 2 EFs for semiconductors may be applied to MEMS manufacturing that uses semiconductor manufacturing tools.

6.2 METHODOLOGICAL ISSUES

6.2.1 Choice of method

6.2.1.1 GASEOUS FLUORINATED COMPOUNDS AND NITROUS OXIDE

Emissions of gaseous fluorinated compounds (FCs) and nitrous oxide from electronics manufacturing vary according to the quantities of the gases used (which vary roughly with the quantity of substrate processed), the identities of the gases used, the processes used, the wafer size (for semiconductors~~)~~, and the type and implementation of emissions control technologies. The choice of methods will depend on data availability and whether the electronics source category is *key*. See Figure 6.1 (Decision tree for estimation of GHG emissions from electronics manufacturing) and Tables 6.3 and 6.4 (Information for sources necessary for completing the tiered emissions estimating methods for electronics manufacturing) for more information.

Continuous (in-situ) emissions monitoring is not currently considered an economically viable means to estimate emissions from the electronics industry; however, greenhouse gas emissions are periodically measured at the process tool exhaust during the development of new processes and tools, generally for centreline process conditions.[3] Such measurements, performed on a large set of processes and averaged at varying levels of

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[3] 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

aggregation, form the basis of the Tier 1 and Tier 2 default emission factors presented in this guidance. They can also be performed by individual facilities and/or their tool suppliers to develop emission factors for specific process recipes or families of recipes when using the Tier 3a method. Finally, 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, as required by the Tier 3b method.

As discussed further below, the precision of the emissions estimate generally improves as one moves from lower to higher Tiers, accounting for more and more site-specific factors. For any single facility, the accuracy of the methods depends, among other things, on the differences between the emission factors of the processes actually used in production and the emission factors of a particular method, and on potential errors in calculating the overall efficiency and uptime of emissions control equipment. These differences and errors are likely to decrease (though not to disappear) as the Tier is increased. Errors in gas consumption measurements and apportioning can also occur and can limit the improvement in precision achieved by characterizing processes at a highly detailed level (e.g., in the Tier 3a method). However, apportioning errors depend on the measurements or model used and, if the guidance provided below is followed, are not expected to become important at the Tier 2 level (e.g., in moving from Tier 2a to Tier 2c). 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 and the electronics category is not *key*, emissions can be estimated using the Tier 1 method based on production figures (surface area of substrate used during the production of electronic devices). However, this approach is the least accurate and should be used only in cases where company-specific gas consumption data is not available. The uncertainty of the Tier 1 method is very high because it does not account for the quantities of the gases consumed (which are only loosely correlated with production), the identities of the gases consumed, the process type, the wafer size (for semiconductors), or the use of emissions control technology.

The Tier 2 methods are expected to be more accurate than the Tier 1 method because they rely on the actual consumption of individual gases and account for the use of emissions control technology. To varying extents, they also distinguish among process types and, for semiconductor manufacturing, wafer sizes. Note that insufficient data was available to calculate Tier 2 factors specifically for MEMS manufacturing; however, the corresponding semiconductor Tier 2 emission factors may be applied unless the MEMS are manufactured using MEMS-specific processes and manufacturing tools. If MEMS-specific manufacturing tools are used, the only higher-Tiered methods available are the Tier 3a and 3b methods.

The Tier 2a method does not distinguish among process types for most GHGs. The exceptions are NF_3 and C_3F_8, for which the Tier 2a method distinguishes between two process types (remote plasma clean vs. all other processes), and N_2O, for which the Tier 2a method distinguishes between two process types for semiconductor manufacturing (TFD and “other”). In addition, the 2a method does not distinguish between wafer sizes for semiconductor or MEMS manufacturing. Because emission factors for semiconductor manufacturing vary significantly based on wafer size, the Tier 2a method should only be used in the case of semiconductor facilities processing multiple substrate sizes where it is not possible to distinguish (apportion) gas consumption between the different substrate sizes. The *2019 Refinement* does not provide a Tier 2a method for the display sub-sector because display manufacturers typically use separate gas supplies for different process types, thus enabling the direct use of the more accurate Tier 2c method without having to apportion gas usage.[4] For the PV sub-sector, it should be noted that the 2006 Tier 2a default factors cannot be applied to the 2019 Tier 2a method because no data was available to calculate default $\gamma_{i,p}$ and $\gamma_{k,i,p}$ values for PV manufacturing. Thus, for PV manufacturing, only the 2019 Tier 2c or the 2019 Tier 3 methods are available.

The 2b method applies only to semiconductor manufacturing and to MEMS manufacturing that uses tools and processes which are similar to those used to manufacture semiconductors. The Tier 2b method is identical to the 2a method except that it provides emission factors that depend on the size of the wafers used for manufacturing ($\leq$200 mm or 300 mm). The Tier 2b method is therefore more accurate than the Tier 2a method for semiconductor and MEMS manufacturing, and it should be used instead of the Tier 2a method when a facility only has one wafer size.

The Tier 2c method is expected to provide more accurate emission estimates than either of the other Tier 2 methods because it distinguishes among all process types for all GHGs, and it also distinguishes between wafer sizes in the semiconductor sub-sector. In addition, the method provides more accurate estimates of the quantities of FCs

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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.

[4] In the case display manufacturers use the same gas supply containers for multiple process types, a gas consumption apportioning model should be used.

exhausted[5] from tools which are connected to emission control systems (see discussion on the $\gamma_{i,p}$ and $\gamma_{k,i,p}$ factors and on the calculation of a_i and $a_{k,i}$ in the next paragraph as well as in the Tier 2a method section, particularly Box 6.3). The Tier 2c method is the only Tier 2 method available for the display and PV sub-sectors. Note that the definitions of process types are specific to each sub-sector: there are 6 distinct process types for the semiconductor sub-sector, 4 process types for the display sub-sector, and 2 process types for the PV sub-sector (see Tier 3a method description for details).

Apportioning is required to track gas consumption to process types. The Tier 2a and 2b methods require only limited apportioning. They are therefore simpler to use than the Tier 2c method, which requires apportioning of all gases to all process types that use those gases. However, the limited apportioning of the Tier 2a and Tier 2b methods significantly increases the uncertainty of their results. Instead of using facility-specific values as the Tier 2c and Tier 3a methods do, the Tier 2a and Tier 2b methods rely on industry average values for (1) the allocation of consumption of each gas to each process type, and (2) in the case of emissions control calculations, the per-tool pre-control emissions of each gas from each process type. These averages are respectively embodied in (1) weighted average emission factors for the process gases and (2) default weighting factors ($\gamma_{i,p}$ and $\gamma_{k,i,p}$) to account for average per-tool emissions from EWC vs. TFD tools for purposes of calculating the impacts of emissions control systems (D_i and $D_{k,i}$). (All of these quantities are discussed further below.) To the extent that the gas consumption patterns at individual facilities depart from these averages, the Tier 2a and Tier 2b methods will be inaccurate for those facilities. There is potential for large errors because emission factors can vary widely among process types, and the shares of each gas flowing to different process types (as well as per-tool emissions for different process types) vary widely among facilities. For these reasons, the Tier 2a and 2b methods should only be used when it is not possible to distinguish (apportion) gas consumption among the larger number of process types identified in the Tier 2c method.

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. However, instead of using default emission factors for relatively broad process types, the Tier 3a method uses, at least in part, measured facility-specific emission factors. This enables the Tier 3a method to capture the variability in emission factors that can occur across processes within the same process type, using the same FC gas, and (for semiconductors) occurring on the same wafer size.[6] In theory, the Tier 3a method could be used to assign an emission factor to each centreline process, recipe, or families of similar recipes (see footnotes 2 and 5 and Tier 3a method discussion), or to assign a specific destruction removal efficiency (DRE) to a particular gas or by-product and emissions control system. It should be noted however that the new Tier 3a method provides more flexibility than the 2006 Tier 3 method in that using it does not require a complete set of measured values (see discussion on the use of 'hybrid' methods in the section on Adapting Tier 2 Methods to Account for Technological Changes). In the case of the Tier 3b method, reporting companies estimate their emissions based on fab[7]-specific 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 system, and 2) the efficacy of the emissions control technologies used with those tools.

Because the new Tier 3b method is based on the measurement of emissions at the end-of-pipe (stack) level, it can be characterized as a 'top-down' method and contrasted to the Tier 2 and Tier 3a methods, which provide a 'bottom-up' approach by estimating emissions based on consumption at the inlet of the process tools. Thus, comparing the results of the various Tier 2 or Tier 3a bottom-up methods to the new top-down Tier 3b method could provide a measure of the accuracy (or inaccuracy) of the methods.

With respect to accounting for emissions control technologies, it should be noted that the *2019 Refinement* includes significant updates to the guidance on how to account for the use of emission control systems. One significant

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[5] In this chapter, the fraction of gas or quantity of gas "exhausted" from process tools refers to the fraction or quantity of that gas that emerges from the tools before abatement is accounted for (i.e., the pre-control emissions). For example, if half of the tools that run etch processes with CHF_3 are equipped with suitable emissions control technologies, then the fraction of CHF_3 exhausted from etch process tools that are equipped with suitable emissions control technologies is 50 percent.

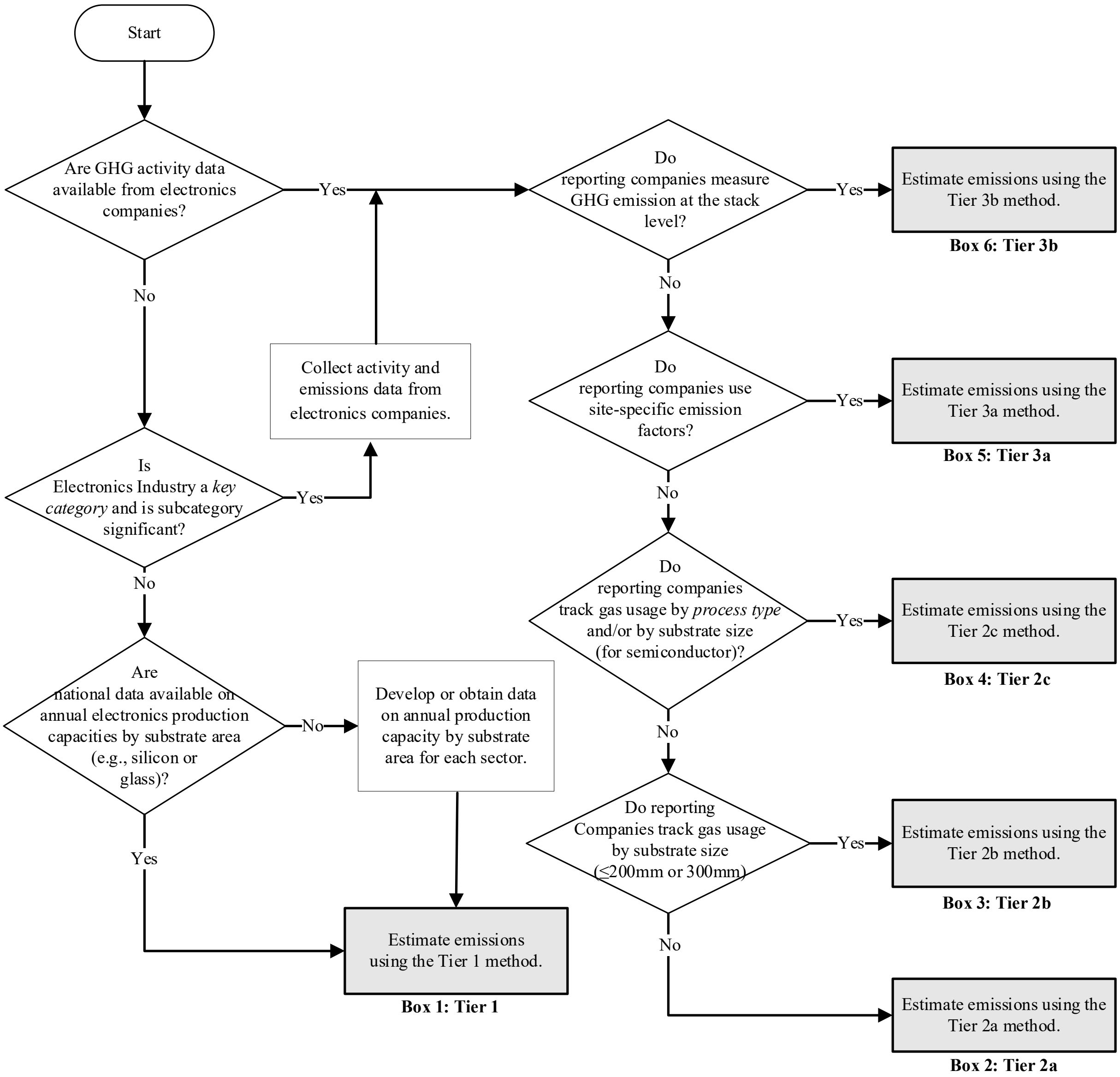
[6] Emission factors for input gas utilisation efficiencies and by-product formation rates can be strongly affected by changes in process variables other than FC gas, substrate size, and process type; these include film and tool type, combination of gases, as well as process recipes variables such as pressure, flow, temperature and plasma power. Further, 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 (see Footnote 2). Emission factors can also be affected by the design of the process reactors and can 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_2O, cleaning a TFD reactor after deposition of silicon nitride using NF_3, etching of a trench in an interconnect structure using C_4F_6, etc.).

[7] 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.

update is the consideration of the uptime of emissions control systems. Another update is guidance to determine the suitability of using particular emissions control 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 emissions control system manufacturers that their emissions control 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. This is important because the efficacy of greenhouse gas emissions control equipment depends on whether it is designed to abate the target gas and on whether it is operated and maintained according to the manufacturer's specifications, especially as regards to not exceeding the individual process gas and total gas flow rates (including any added purge gases) as stated by the emissions control equipment supplier. Guidance is also provided for using site-specific (measured) destruction removal efficiencies to claim DREs that may be different 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 the accuracy of emissions estimates. If default emission factors are not available under Tier 2 (e.g. if a new wafer size or process type is introduced), or when a default emission factor is known to substantially differ from a facility-specific emission factor, inventory compilers can undertake process emissions characterization under Tier 3a and measure (1-U) and B factors for those new processes without defaults (or with an emission factor different than the default) while using Tier 2 defaults for existing processes (hybrid approach). 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.

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



For semiconductor 450 mm substrate size, facilities should test and develop measured emission factors (Tier 3a). Tier 2a should not be used for 450 mm. 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. See section "Adapting Tier 2 Methods to account for technological changes" for more details.

Tables 6.3 (for gaseous FCs) and 6.4 (for liquid FCs) present the information necessary for completing emissions estimates for each tiered method and list all the variables that appear in the equations of each method. Depending on the method, variables may either be default values (denoted as 'D' and provided within this document (see section 6.2.2)), or variables may be measured (denoted as 'Me'), modelled (denoted as 'Mo'), or calculated (denoted as 'C' for every variable appearing on the left side of the equal sign in an equation).

Table 6.3 (Updated)
Information sources necessary for completing the tiered emissions estimating methods for gaseous FCs for Electronics Manufacturing

Note: The names of the variables have been simplified for the purpose of Table 6.3; please refer to the equations in each tiered methodology for the complete definitions of the variables and their units.
Legend: (Me) = measured; (Mo) = modelled (calculated but no equation specified in this chapter); (D) = default factors from guidance; (C) = calculated using an equation in this chapter.
* These variables are applicable to both sampling period and total year.

	Variables	Tier 1	Tier 2			Tier 3	
			2a	2b	2c	3a	3b
Production	Annual production	P (Me/Mo)					
	Fraction of PV manufacture that uses FC gases	F_{PV} (Me/Mo)					
	δ = 1 when applied to PV industry and zero when applied to either semiconductor or TFT-Display industries, dimensionless	δ (D)					
	Total number of tools that use gas i to run process type p (e.g., chamber cleaning processes)		$n_{i,p}$, $n_{k,i,p}$ (Me)	$n_{i,p}$, $n_{k,i,p}$ (Me)	$n_{i,p}$, $n_{k,i,p}$ (Me)	$n_{i,p}$, $n_{k,i,p}$ (Me)	$n_{i,p}$, $n_{k,i,p}$ (Me)
	Number of tools that use gas i to run process type p and that are equipped with suitable emissions control technologies		$n_{i,p,a}$, $n_{k,i,p,a}$ (Me)	$n_{i,p,a}$, $n_{k,i,p,a}$ (Me)	$n_{i,p,a}$, $n_{k,i,p,a}$ (Me)	$n_{i,p,a}$, $n_{k,i,p,a}$ (Me)	$n_{i,p,a}$, $n_{k,i,p,a}$ (Me)
	Total number of tools that use gas i to run reference process type q (e.g., etch and/or wafer cleaning (EWC) processes)		$m_{i,q}$, $m_{k,i,q}$ (Me)	$m_{i,q}$, $m_{k,i,q}$ (Me)			$m_{i,q}$, $m_{k,i,q}$ (Me)
	Number of tools that use gas i to run reference process type q and that are equipped with suitable emissions control technologies		$m_{i,q,a}$, $m_{k,i,q,a}$ (Me)	$m_{i,q,a}$, $m_{k,i,q,a}$ (Me)			$m_{i,q,a}$, $m_{k,i,q,a}$ (Me)
Process Gas Entering Tool	Annual consumption of gas		C_i(C)	C_i (C)	$C_{i,p}$ (C)	$C_{i,p}$ (C)	$C_{i,f}$ (Me/Mo)
	Inventory of input gas stored in containers at the beginning of the reporting year		IB_i (Me)	IB_i (Me)	IB_i (Me)	IB_i (Me)	IB_i (Me)
	Inventory of input gas stored in containers at the end of the reporting year		IE_i (Me)	IE_i (Me)	IE_i (Me)	IE_i (Me)	IE_i (Me)
	Acquisitions of input gas during the year		A_i (Me)	A_i (Me)	A_i (Me)	A_i (Me)	A_i (Me)
	Transfers of input gas		T_i (C)	T_i (C)	T_i (C)	T_i (C)	T_i (C)
	Heel factor		$h_{i,c}$ (D/Me)	$h_{i,c}$ (D/Me)	$h_{i,c}$ (D/Me)	$h_{i,c}$ (D/Me)	$h_{i,c}$ (D/Me)
	Number of containers		$N_{i,c}$ (Me)	$N_{i,c}$ (Me)	$N_{i,c}$ (Me)	$N_{i,c}$ (Me)	$N_{i,c}$ (Me)
	Full capacity of containers		$F_{i,c}$ (Me)	$F_{i,c}$ (Me)	$F_{i,c}$ (Me)	$F_{i,c}$ (Me)	$F_{i,c}$ (Me)
	Total number of container types		M (Me)	M (Me)	M (Me)	M (Me)	M (Me)
	Apportioning factor		$\Phi_{i,p}$ (Me/Mo)	$\Phi_{i,p}$ (Me/Mo)	$\Phi_{i,p}$ (Me/Mo)	$\Phi_{i,p}$ (Me/Mo)	

Table 6.3 (Updated) (continued)
Information sources necessary for completing the tiered emissions estimating methods for gaseous FCs for Electronics Manufacturing

Note: The names of the variables have been simplified for the purpose of Table 6.3; please refer to the equations in each tiered methodology for the complete definitions of the variables and their units.
Legend: (Me) = measured; (Mo) = modelled (calculated but no equation specified in this chapter); (D) = default factors from guidance; (C) = calculated using an equation in this chapter.
* These variables are applicable to both sampling period and total year.

	Variables	**Tier 1**	**Tier 2**			**Tier 3**	
			2a	**2b**	**2c**	**3a**	**3b**
Process	Emission Factor	EF_i (D)					
	Use rate of gas		U_i (D)	U_i (D)	$U_{i,p}$ (D)	$U_{i,p}$ (Me)	
	Byproduct emission factor		$B_{k,i}$ (D)	$B_{k,i}$ (D)	$B_{k,i,p}$ (D)	$B_{k,i,p}$ (Me)	
Downstream Emissions Control	Destruction Removal Efficiency (DRE)		d_i, d_k (D)	d_i, d_k (D)	d_i, d_k (D)	d_i, d_k (D/Me)	d_i , d_k (D/Me)
	Overall reduction of emissions		D_i, $D_{k,i}$ (C)	D_i, $D_{k,i}$ (C)	$D_{i,p}$, $D_{k,i,p}$ (C)	$D_{i,p}$, $D_{k,i,p}$ (C)	
	Mass fraction of F_2 in process exhaust gas that is converted into CF_4 by direct reaction with hydrocarbon fuel in a combustion emissions control system.		$AB_{CF4,F2}$ (D)	$AB_{CF4,F2}$ (D)	$AB_{CF4,F2}$ (D)	$AB_{CF4,F2}$ (D)	
	Ratio of uncontrolled emissions per-tool from tools running weighted process types p (e.g., chamber cleaning processes) to uncontrolled emissions per-tool from process tools running reference process types q (e.g., EWC processes)		$\gamma_{i,p}$, $\gamma_{k,i,p}$ (D)	$\gamma_{i,p}$, $\gamma_{k,i,p}$ (D)			$\gamma_{i,p}$, $\gamma_{k,i,p}$ (D)
	Estimate of the fraction of gas exhausted from process tools equipped with suitable emissions control technologies		a_i, $a_{k,i}$ (C)	a_i, $a_{k,i}$ (C)	$a_{i,p}$, $a_{k,i,p}$ (C)	$a_{i,p}$, $a_{k,i,p}$ (C)	$a_{i,f}$, $a_{k,i,f}$ (C)
	Uptime factor of emissions control systems		UT (C)	UT (C)	UT_p (C)	UT_p (C)	UT_f (C)*
	Total time that emissions control system connected to process tool(s) in the plant is not in operational mode when at least one of the manufacturing tools connected to emissions control system is in operation		Td_n (Me)	Td_n (Me)	$Td_{n,p}$ (Me)	$Td_{n,p}$ (Me)	$Td_{n,f}$ (Me)*
	Total time during which emissions control system has at least one associated manufacturing tool in operation		TT_n (Me)	TT_n (Me)	$TT_{n,p}$ (Me)	$TT_{n,p}$ (Me)	$TT_{n,f}$ (Me)*

TABLE 6.3 (UPDATED) (CONTINUED)
INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR GASEOUS FCS FOR ELECTRONICS MANUFACTURING

Note: The names of the variables have been simplified for the purpose of Table 6.3; please refer to the equations in each tiered methodology for the complete definitions of the variables and their units.
Legend: (Me) = measured; (Mo) = modelled (calculated but no equation specified in this chapter); (D) = default factors from guidance; (C) = calculated using an equation in this chapter.
* These variables are applicable to both sampling period and total year.

	Variables	**Tier 1**	**Tier 2**			**Tier 3**	
			2a	**2b**	**2c**	**3a**	**3b**
Stack Test Specific	Flow rate of stack system during the sampling period						Q_s (Me)
	Molecular weight of gas						MW_i, MW_k (D)
	Standard molar volume of gas						SV (D)
	Average concentration of input gas in stack system during sampling						$X_{i,s,m}$, $X_{k,s,m}$ (Me)
	Length of time interval m in the FTIR sampling period						Δt_m (Me)
	Total number of time intervals m in sampling period						N (C)
	Consumption of input gas during the sampling period						$Activity_{i,f}$ (Me)
	Facility-specific emission factor						$EF_{i,f}$, $EF_{k,f}$ (C)
Emissions	Emissions of FC gases or N_2O	$\{E_i\}_n$ (C)					
	Emissions of unreacted input gas		E_i (C)	E_i (C)	E_i (C)	E_i (C)	$EA_{i,f}$, $ES_{i,s}$ (C)
	Emissions of by-products		BPE_k (C)	BPE_k (C)	BPE_k (C)	BPE_k (C)	$EA_{k,f}$, $ES_{k,s}$ (C)
	Emissions of CF_4 from hydrocarbon-fuel-based combustion emissions control systems		$EAB_{i,CF4}$ (C)	$EAB_{i,CF4}$ (C)	$EAB_{i,CF4}$ (C)	$EAB_{i,CF4}$ (C)	

TABLE 6.4 (UPDATED)
INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR LIQUID FCS FOR ELECTRONICS MANUFACTURING

Legend: (Me) = measured; (Mo) = modelled (calculated but no equation specified in this chapter); (D) = default factors from guidance; (C) = calculated using an equation in this chapter.
* These variables are applicable to both sampling period and total year.

	Tier 1	Tier 2
Annual production either in m^2 of substrate used during the production of electronic devices (for heat transfer fluid applications) or in thousands of packaged devices (for testing, packaging and soldering)	P (Me)	
Emission factor for fluorinated liquid aggregate emissions either per m^2 of substrate consumed during the period (kg/m^2, for heat transfer fluid applications), or per thousand packaged devices (kg/kpcs, for testing, packaging and soldering)	EF_i (D)	
Density of fluorinated liquid		ρ_i (Me)
Inventory of fluorinated liquid in containers other than equipment at the beginning of the reporting year		I_{it-1} (Me)
Acquisitions of fluorinated liquids during the reporting year, 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		$P_{i,t}$ (Me)
Total nameplate capacity of equipment that uses fluorinated liquids and that is newly installed in the facility during the reporting year		$N_{i,t}$ (Me)
Total nameplate capacity of equipment that uses fluorinated liquids and that is removed from service in the facility during the reporting year		$R_{i,t}$ (Me)
Inventory of fluorinated liquids in containers other than equipment at the end of the reporting year		$I_{i,t}$ (Me)
Disbursements of fluorinated liquids, including amounts returned to chemical suppliers, sold with or inside of equipment, and sent off-site for verifiable recycling or destruction		$D_{i,t}$ (Me)
Emissions of fluorinated liquid	FC_i (C)	FC_i (C)

TIER 1 METHOD – DEFAULT EMISSION FACTORS BASED ON PRODUCTION

The Tier 1 method is the least accurate estimation method and should be used only in cases where facility-specific 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 N_2O emissions with an estimated but uncertain break-out among specific gases. Estimates are made simultaneously for all the gases listed in Table 6.6, and the Tier 1 method can only be used if these gases are reported as a complete set. For each class (sub-sector) 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 square meters (m^2)). 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.

EQUATION 6.1 (UPDATED)
TIER 1 METHOD FOR ESTIMATION OF THE SET OF GHG EMISSIONS

$$\{E_i\}_n = \{EF_i \bullet P \bullet [F_{PV} \bullet \delta + (1-\delta)]\}_n \quad (i = 1, \ldots, n)$$

Where:

$\{E_i\}_n$ = emissions of fluorinated compound gas i (FC_i) or N_2O, kg for semiconductors and MEMS, g for display and PV

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 ({12} for semiconductors, {6} for display, {3} for MEMS, and {2} for PV, see Table 6.6). The estimates are only valid if made and reported for all members of the set using this Tier 1 methodology

EF_i = 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^2. See default factors of Table 6.6

P = annual production, m^2 of substrate used as measured by the 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 FC gases, fraction

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

i = input gas

This method does not account for actual gas consumption or for differences in emission factors 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 6.6. 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_4 to estimate the emissions of CF_4 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.)

GAS CONSUMPTION AND APPORTIONING FOR TIERS 2 AND 3

In using the Tier 2 and Tier 3a methods, input gas consumption (C_i) should be determined and apportioned to specific process types ($C_{i,p}$). Where the Tier 2c or 3a methods are used to estimate emissions from a semiconductor facility that manufactures on multiple wafer sizes, gas consumption should be apportioned to specific wafer sizes as well. In this situation, the equations below can be used twice, substituting "wafer size" for "process" as a first step and then using the equation again for "process". Total annual input gas i consumption (C_i) on a facility basis for each fluorinated compound and N_2O is calculated using Equation 6.2 below.

EQUATION 6.2 (NEW)
CONSUMPTION OF INPUT GAS I

$$C_i = \left(IB_i - IE_i + A_i - T_i\right)$$

Where:

C_i = annual consumption of input gas i (site specific), kg per year

IB_i = inventory of input gas i stored in containers at the beginning of the reporting year, including heels, 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, 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, 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, kg

i = input gas.

Transfers (T_i) are calculated using Equation 6.3.

EQUATION 6.3 (NEW)
TRANSFERS OF INPUT GAS I

$$T_i = \sum_{c=1}^{M} h_{i,c} \bullet N_{i,c} \bullet F_{i,c}$$

Where:

T_i = transfers of input gas i through sales or other transactions during the reporting year for the reporting facility, including heels in containers returned by the electronics manufacturing fab to the gas distributor, kg

$h_{i,c}$ = gas-specific heel factor for input gas i and container size and type c, fraction. A default $h_{i,c}$=0.1 may be used instead of developing gas-specific, container-specific factors

$N_{i,c}$ = number of containers of size and type c used at the reporting facility and returned to the gas distributor containing the standard heel of input gas i

$F_{i,c}$ = full capacity of containers of size and type c containing input gas i, kg

i = input gas

c = size and type of gas container

M = total number of different sized container types for the reporting facility. If only one size and container type is used for an input gas i, M = 1

A site-specific heel factor for each type of gas and container used in a facility ($h_{i,c}$) 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 reporting facility uses less than 50 kg of an FC gas or N_2O in one reporting year, inventory compilers may assume that any $h_{i,c}$ for that FC gas or N_2O is equal to zero.

For the Tier 2 and Tier 3a methods, varying degrees of gas use apportioning are required. For the semiconductor sub-sector, the Tier 2a and 2b methods require apportioning of NF_3 and C_3F_8 consumption between the remote plasma clean (RPC) process type and other NF_3- or C_3F_8-using process types, while N_2O is apportioned between the N_2O TFD process type and "Other" N_2O-using process types. The Tier 2c (for the semiconductor, MEMS, and display sub-sectors) and the Tier 3a (for all sub-sectors) methods require apportioning for each input gas i and each process type p. Apportioning is calculated using Equation 6.4.

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

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

Where:

$C_{i,p}$ = annual amount of input gas i consumed by the reporting facility for process type p, kg

$\Phi_{i,p}$ = process type p-specific apportioning factor for input gas i, fraction

C_i = annual consumption of input gas i for the reporting facility, as calculated using Equation 6.2, kg

i = input gas

To minimize apportioning uncertainty and increase accuracy, it is *good practice* to implement a gas consumption monitoring system using direct measurement to apportion gas use at the process type-, stack system- or facility-level as appropriate. This can be achieved by various methods including monitoring and integrating the signal of Mass Flow Controllers (MFCs) and using weigh scales; however, it is noted that measurement to specific tools or processes may not be feasible. If gas consumption measurement at the process level is not deemed feasible for a particular facility, apportioning factors ($\Phi_{i,p}$) can be calculated using a site-specific engineering model. This model should be based on a quantifiable metric, such as substrate passes or substrate starts. To verify the apportioning model, it is *good practice* to demonstrate its precision and accuracy as follows:

(1) Demonstrate that the FC gases and N_2O apportioning factors are developed using calculations that are repeatable, which means that the variables used in the formulas for the facility's engineering model for gas apportioning factors should be based on observable and measurable quantities that govern gas consumption rather than engineering judgment about those quantities or gas consumption. Note that research and development (R&D) and tool commissioning activities may be excluded from the apportioning calculations, but that gas purchases in support of these activities should be included in the emissions calculation. In the event of the introduction of new manufacturing technologies or new gases, this demonstration should be repeated.

(2) Demonstrate the accuracy of the site-specific apportioning model by comparing the actual amount of input gas i consumed and the modelled amount of input gas i consumed in the facility, by:

   (i) Analysing actual and modelled gas consumption for a sustained period (at least 30 days) when the fab is at a representative operating level (at least 70 percent of the average production rate for the year in terms of monthly substrate starts). In the event of the introduction of new technologies or substrate size this analysis should be repeated.

   (ii) Comparing the actual gas consumed to the modelled gas consumed for the highest use fluorinated compound (or compounds) used in multiple process types at the facility (e.g., NF_3 use in remote plasma clean and other processes).

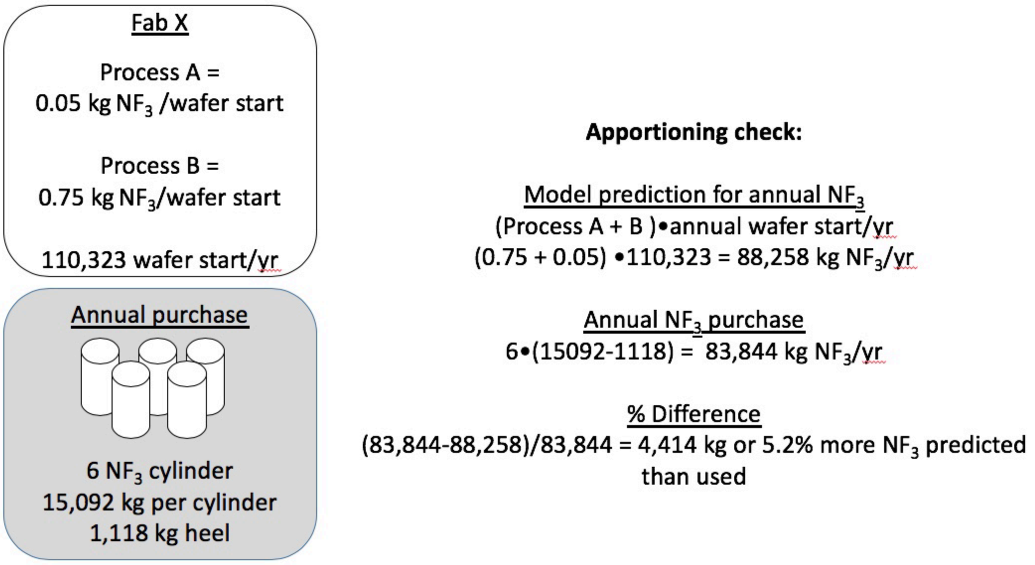
   (iii) Demonstrating that the comparison performed for the largest quantity of gas(es), on a mass basis, consumed in the facility, does not result in a difference between the actual and modelled gas consumption that exceeds 20 percent relative to actual gas consumption.

   (iv) If 20 percent is not achieved, the model should be revised until the difference between actual and the modelled gas consumption does not exceed 20 percent.

Note that inventory compilers may use a combination of apportioning factors developed using a facility-specific engineering model and apportioning factors developed through the use of direct measurement.

Box 6.1 provides an example of a site-specific apportioning model verification.

BOX 6.1 (NEW)
SITE-SPECIFIC APPORTIONING MODEL VERIFICATION EXAMPLE



Fab X

Process A =
0.05 kg NF_3 /wafer start

Process B =
0.75 kg NF_3/wafer start

110,323 wafer start/yr

Annual purchase

6 NF_3 cylinder
15,092 kg per cylinder
1,118 kg heel

Apportioning check:

Model prediction for annual NF_3
(Process A + B)•annual wafer start/yr
(0.75 + 0.05) •110,323 = 88,258 kg NF_3/yr

Annual NF_3 purchase
6•(15092-1118) = 83,844 kg NF_3/yr

% Difference
(83,844-88,258)/83,844 = 4,414 kg or 5.2% more NF_3 predicted than used

TIER 2 METHODS – DEFAULT EMISSION FACTORS BASED ON GAS CONSUMPTION

Tier 2a Method

The Tier 2a method is applicable to semiconductor manufacturing and to MEMS manufacturing that is carried out using tools and processes similar to those used to manufacture semiconductors (for further details see discussion in the Choice of method section, in particular footnote 3). As discussed above, the Tier 2a method does not distinguish between wafer sizes or among process types for most FCs; however, the Tier 2a method does provide different default emission factors for C_3F_8 RPC vs. other C_3F_8-using processes, for NF_3 RPC 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 and NF_3 should be apportioned between RPC and other processes, and consumption of N_2O should be apportioned between TFD and "Other" N_2O-using processes, as applicable to each reporting site.

The Tier 2a method uses the default emission factors provided in Table 6.7, which represent average utilisation efficiencies of the gases used in manufacturing processes (U_i) and the formation of by-products during the use of each input gas i ($B_{k,i}$). The other default factors used for the Tier 2a method include the destruction removal efficiency of gases i and by-products k (d_i, d_k - see Table 6.17) and the ratio of per-tool uncontrolled emissions of gases i (and by-products k) from TFD process tools to per-tool uncontrolled emissions of gases i (and by-products k) from EWC process tools ($\gamma_{i,p}$, $\gamma_{k,i,p}$ - see Table 6.8).

The Tier 2a method also uses site-specific data on gas consumption and emissions control. Inventory compilers using the Tier 2a method should directly communicate with industry to gather consumption and emissions control-related data and to ensure that reductions are not attributed to emissions control devices unless the devices are installed and used in accordance with the guidance provided in section 6.2.2.1. Inventory compilers should note that the consumption of gas i (Ci) takes into account the heel factor (hi,c), 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 (see Section on Gas Consumption and Apportioning).

Total Tier 2a emissions are calculated using Equations 6.5, 6.6, and 6.7 below, and are equal to the sum of emissions from all unreacted gases i used in the production process (E_i), plus emissions of all by-products k (BPE_k) resulting from the conversion of all input gases i used during production, plus emissions of CF_4 from hydrocarbon-fuel-based combustion emissions control systems ($EAB_{i,CF4}$). However, note that $EAB_{i,CF4}$ may be set equal to zero if the emissions control equipment manufacturer can certify that reactions between hydrocarbon fuel and F_2 to form CF_4 are not occurring within their emissions control systems (i.e. certify that $AB_{i,CF4} = 0$).

EQUATION 6.5 (UPDATED)
EMISSIONS OF INPUT GAS I

$$E_i = C_i \bullet \left(1 - U_i\right) \bullet \left(1 - D_i\right)$$

Where:

E_i = emissions of unreacted input gas i, kg

C_i = consumption of input gas i, kg

U_i = use rate of gas i (fraction destroyed or transformed in process), fraction

D_i = overall reduction of mass of gas i emissions, site-specific fraction, calculated per Equation 6.8

i = input gas or, for NF_3, C_3F_8, and N_2O, input gas and process type combination

EQUATION 6.6 (UPDATED)
BY-PRODUCT EMISSIONS

$$BPE_k = \sum_i [C_i \bullet B_{k,i} \bullet (1 - D_{k,i})]$$

Where:

BPE_k = emissions of by-product k generated from the conversion of all input gases i, kg

C_i = consumption of input gas i, kg

$B_{k,i}$ = emission factor for by-product k generated from input gas i, kg of by-product gas k created/kg of gas i consumed

$D_{k,i}$ = overall reduction of mass of emissions of by-product gas k formed from input gas i, site-specific fraction, calculated per Equation 6.9

i = input gas or, for NF_3, C_3F_8, and N_2O, input gas and process type combination

k = by-product gas

BOX 6.2 (NEW)
FLUORINATED GREENHOUSE GAS BY-PRODUCTS

As discussed briefly in the introduction, the formation of fluorinated GHG by-products resulting from the decomposition of input gases or from the reaction with the materials being etched or cleaned should be taken into account. To this effect, by-product emission factors ($B_{CF4,i}$, $B_{C2F6,i}$, $B_{C3F8,i}$, $B_{C4F6,i}$, $B_{C4F8,i}$, $B_{C5F8,i}$, $B_{CH3F.i}$ $B_{CH2F2,i}$, and $B_{CHF3,i}$, emission factors indicating the mass ratio of by-product produced from the use of input gas i) are included as part of the default emission factors tables for the Tier 2 methods. In some cases, perfluorinated carbon by-product emission factors are provided, even when the etching or cleaning gas i itself contains fluorine but does not contain carbon (e.g. NF_3, SF_6, F_2). 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 expected to be formed during the process.

As noted in Box 6.2 the formation of FC gas by-products such as CF_4, C_2F_6, CH_3F, CH_2F_2, and CHF_3 can occur when etching or cleaning carbon-containing films, even when input gases do not contain carbon (e.g. NF_3, SF_6, F_2). 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 $B_{k,i}$ factors may be set equal to zero in Equation 6.6. 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 $B_{k.i}$ 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.

Emissions and emission reductions from emission control devices

When NF_3 is used in RPC processes or F_2 is used as an input gas and when hydrocarbon-fuel-based combustion emissions control technology is used, direct reaction with hydrocarbon fuel and F_2 (including F_2 resulting from the decomposition of NF_3 in RPC processes) to form CF_4 can occur. Unless the emissions control system manufacturer (referred to below as the "original equipment manufacturer" or "OEM") or electronics manufacturer can certify that the rate of conversion from F_2 to CF_4 or from NF_3 to CF_4 is <0.1 percent on a mass basis, Equation 6.7 should be used to estimate the amount of CF_4 produced within and emitted from the emissions control equipment.

EQUATION 6.7 (NEW)
BY-PRODUCT EMISSIONS FROM HYDROCARBON FUELLED COMBUSTION EMISSIONS CONTROL SYSTEMS

$$EAB_{i,CF_4} = C_i \bullet (1 - U_i) \bullet (1 - \eta) \bullet AB_{i,CF_4}$$

Where:

i = input gas (i = only NF_3 used in RPC processes or F_2 for the purpose of Equation 6.7)

$EAB_{i,CF4}$ = emissions of CF_4 from hydrocarbon-fuel-based combustion emissions control systems when direct reaction with hydrocarbon fuel and fluorinated species is not certified not to occur by the emissions control OEM or electronics manufacturer, kg

C_i = consumption of gas i (i = only NF_3 used in RPC processes or F_2 for the purpose of Equation 6.7), kg

U_i = use rate of gas i, fraction destroyed or transformed in process

η of ratio of emissions control systems certified not to form CF_4 within emissions control systems to the total number of emissions control systems in the facility, site-specific fraction

$AB_{i,CF4}$ (i = only NF_3 used in RPC processes or F_2 for the purpose of Equation 6.7) = mass fraction of NF_3 used in RPC processes or F_2 in process exhaust gas that is converted into CF_4 by direct reaction with hydrocarbon fuel and F_2 gas in a combustion emissions control system. $AB_{i,CF4}$ is set to zero if the emissions control OEM or electronics manufacturer can certify that the rate of conversion from F_2 to CF_4 or from NF_3 to CF_4 is <0.1 percent; otherwise, a default value of $AB_{NF3,CF4} = 0.093$ or $AB_{F2,CF4} = 0.116$ should be used.

Inventory compilers should calculate the overall reductions in emissions of process gas i and by-product k (D_i, $D_{k,i}$) based on site-specific information using Equations 6.8 and 6.9, factoring in the mass fraction of gas i and by-product k exhausted from process tools equipped with suitable emissions control technologies (a_i, $a_{k,i}$), the destruction removal efficiency of gas i and by-product k (d_i, d_k), and the average uptime of emissions control systems (UT).

EQUATION 6.8 (NEW)
EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL TECHNOLOGY FOR GAS I

$$D_i = a_i \bullet d_i \bullet UT$$

Where:

D_i = overall reduction of mass of gas i emissions, site-specific fraction

a_i = estimate of the fraction of gas i emitted from process tools equipped with suitable emissions control technologies, site-specific fraction as determined in Equation 6.10 or Equation 6.18, as applicable

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

UT = average uptime factor of all emissions control systems, site-specific fraction, calculated per Equation 6.12

i = input gas, or, for NF_3, C_3F_8, and N_2O, input gas and process type combination

EQUATION 6.9 (NEW)
EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL TECHNOLOGY FOR BY-PRODUCT K

$$D_{k,i} = a_{k,i} \bullet d_k \bullet UT$$

Where:

$D_{k,i}$ = overall reduction of mass of emissions of by-product k formed from input gas i, site-specific fraction

$a_{k,i}$ = estimate of the fraction of by-product k that is formed from input gas i and that is exhausted from process tools equipped with suitable emissions control technologies, site-specific fraction, as determined in Equation 6.11 or Equation 6.19, as applicable

d_k = Destruction Removal Efficiency (DRE) for by-product k, fraction

UT = average uptime factor of all emissions control systems, site-specific fraction, calculated per Equation 6.12

i = input gas, or, for NF_3, C_3F_8, and N_2O, input gas and process type combination

k = by-product gas

Calculation of a_i and $a_{k,i}$ using the default weighting factors $\gamma_{i,p}$ and $\gamma_{k,i,p}$

When using the Tier 2a method, inventory compilers should calculate the fractions of gas i and by-products k formed from gas i (based on mass) exhausted from process tools equipped with suitable emissions control technologies (a_i and $a_{k,i}$). “Suitable” means that an emissions control technology is capable of abating a particular gas to a minimum destruction removal efficiency in a site-specific worst-case scenario (please see Section 6.2.2.1 on Emissions Control Technology Factors for more details).

For NF_3 and C_3F_8 used in RPC processes, and for N_2O used in either TFD or “other” processes, inventory compilers should use Equations 6.18 and 6.19 to estimate the fractions of the input gas and associated by-product abated for each of those process types ($a_{i,p}$ and $a_{k,i,p}$). For other input-gas and process-type combinations, inventory compilers using the Tier 2a method (or the Tier 2b or Tier 3b method) should use Equations 6.10 and 6.11 to estimate the fractions of input gas and by-product abated across multiple process types (a_i and $a_{k,i}$).

In all of these equations (6.10, 6.11, 6.18, and 6.19), the fraction of pre-control emissions that is exhausted to emissions control systems is approximated using the fraction of the total number of tools that exhaust to emissions control systems.[8] This approximation is expected to be reasonably good by itself if all the tools are running the same process type (e.g., chamber cleaning vs. etching). However, the approximation may be poor by itself if the tools are running different process types, because emissions per tool can vary greatly across different process types. In Equations 6.10 and 6.11, the fraction of emissions destroyed is estimated across different process types. Thus, in these equations, new default weighting factors ($\gamma_{i,p}$ for input gases and $\gamma_{k,i,p}$ for by-product gases, provided in Table 6.8) are applied to tools that run chamber cleaning processes to increase the accuracy of the estimate.

As discussed in Box 6.3, the gamma factors reflect the ratio of the uncontrolled emissions per tool of gas i or by-product k from tools running the weighted process type “p” to the uncontrolled emissions per tool of gas i or by-product k from tools running the reference process type “q.” When Equation 6.10 or 6.11 is used for the Tier 2a or Tier 2b method, p includes the in-situ plasma cleaning (IPC) and the in-situ thermal cleaning (ITC) process types, while q consists of the etching and wafer cleaning (EWC) process type. (These terms include additional

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[8] If a facility monitors input gas consumption by tool (e.g., using MFCs), this information rather than tool counts may be used to calculate $a_{i,p}$ and $a_{k,i,p}$. Similarly, if a facility using the 3b method monitors or otherwise apportions gas consumption by process type, Equations 6.18 and 6.19 may be used to estimate $a_{i,p}$ and $a_{k,i,p}$ for all process types at the facility.

process types for Tier 3b; see the definitions of the terms "p" and "q" in Equations 6.10 and 6.11. [9]) For Tiers 2a and 2b, taking gamma values into account is necessary when (1) an input gas is consumed (or a by-product k is produced) both by chamber cleaning processes and by EWC processes, (2) the use of the input gas is not apportioned between chamber cleaning processes and EWC processes, and (3) the fractions of tools equipped with emissions control technologies are different for chamber cleaning processes and EWC processes. To calculate a_i and $a_{k,i}$, inventory compilers should use Equations 6.10 and 6.11 and the default gamma factors, as well as the numbers of tools in the reporting facility using gas i or producing by-product k from gas i while running process type p or q ($n_{i,p}$, $m_{i,q}$, $n_{k,i,p}$, $m_{k,i,q}$), and the numbers of those tools equipped with suitable emissions control technology for gas i or by-product k while running process type p or q ($n_{i,p,a}$ $m_{i,q,a}$, $n_{k,i,p,a}$, $m_{,k,i,q,a}$).

For each gas where a value for $\gamma_{i,p}$ or $\gamma_{k,i,p}$ exists, Table 6.8 provides gamma values relating per-tool emissions from the weighted process type p to per-tool emissions from the reference process type q. The gamma value column selected by a facility depends on the gas(es) emitted by the facility and the process(es) used by the facility. The gamma value row depends on the method used by the facility (Tier 2a, 2b, or 3b), whether the gas is emitted as an input gas or by-product, and (for Tier 2b and 3b), the wafer size. For example, a facility emitting CF_4 from both IPC processes and ITC processes would use a gamma value from the second column from the left in Table 6.8. If the facility were using the Tier 2a method to estimate emissions of CF_4 as an input gas, it would use the γ_i value in the row immediately below the "Tier 2a" title row in the table. The corresponding tool counts $n_{i,p}$ would be the total numbers of tools that emit CF_4 as an input gas and that run IPC and ITC processes, respectively, and the corresponding tool counts $n_{i,p,a}$ would be the total numbers of tools that emit CF_4 as an input gas, that run IPC and ITC processes, respectively, and that are abated.

Where a facility requires a gamma value for a gas-process type combination that is not covered by the table (e.g., c-C_4F_8 IPC), the facility should use a default gamma value of 10.

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[9] For the Tier 3b method (stack testing), gamma values are also provided for remote plasma clean (RPC) for FCs and for thin-film deposition (TFD) for N_2O. The Tier 2a and 2b methods require apportioning between TFD and "Other" N_2O processes and between RPC and other FC processes and therefore do not need gamma values for TFD and RPC.

BOX 6.3 (NEW)
THE IMPORTANCE AND LIMITATIONS OF THE DEFAULT GAMMA VALUES FOR CALCULATING A_I AND $A_{K,I}$

To estimate the fraction of an FC abated when that FC is exhausted from both chamber cleaning processes and EWC processes, the Tier 2a, Tier 2b, and Tier 3b methods apply default weighting factors ($\gamma_{i,p}$ and $\gamma_{k,i,p}$) to the numbers of abated and unabated tools running chamber cleaning processes (see Equations 6.10 and 6.11). (As discussed above, the Tier 3b method also applies default weighting factors to the numbers of abated and unabated tools running N_2O-using TFD processes.) These default weighting factors have been introduced in the Refinement because, for most FCs, the Tier 2a, Tier 2b, and Tier 3b methods do not otherwise track per-tool emissions by process type (i.e., through apportioning), and per-tool emissions can vary significantly between process types. For example, C_2F_6 input gas flows (and emissions) for chamber cleaning processes can typically be in the order of one or more litres per minute while C_2F_6 input gas flows (and emissions) for etching processes are only typically in the order of one tenth to a few tenth of litres per minute. These differences are reflected in the default gamma values, which range from 1.4 to 26 for FC input gases, for example. Not accounting for such differences (that is, using unweighted tool counts) could result in large errors in the emissions estimate when the fraction of process tools equipped with emissions control technologies is different for different process types. *(Note: Where the Tier 2a and 2b methods do track emissions and emission reductions by process type, that is, for NF_3 and C_3F_8 used in RPC and for N_2O used in either TFD or "other" processes, Equations 6.18 and 6.19 should be used to calculate the fractions of input gas and by-products abated for each of those process types.)*

Default gamma values have been calculated based on the consumption patterns of representative semiconductor manufacturing facilities, accounting for the emissions of unreacted gases i and by-products k as well as for the number of tools emitting gases i or by-products k in such facilities. The default gamma values therefore represent industry averages. However, the gammas found for individual facilities are highly variable depending on gas usage patterns at those facilities. For example, two facilities could have similar numbers of etching tools and use similar total quantities of a particular FC in their etching processes. However, one of the facilities may concentrate their use of that FC in a relatively small subset of their etching tools (e.g., because that FC is the only gas used in that subset of tools), while the other facility may spread their use of that FC across all of their etching tools (e.g., because that FC is used in combination with other FCs in the tools). The per-tool emissions of the FC from etching for the first facility would be much higher than the per-tool emissions of the FC from etching at the second. If the per-tool emissions from TFD tools were the same at both facilities, the first facility's gamma factor (ratio of per-tool emissions from TFD tools to per-tool emissions from etch tools) would be much smaller than the second facility's gamma factor. As a result of such variability, the gamma values are highly uncertain (see Table 6.22) and can lead to errors in emissions estimates.

Because actual (site-specific) $\gamma_{i,p}$ and $\gamma_{k,i,p}$ values may significantly differ from the defaults used in the Tier 2a and 2b methods, and because – as a result – the Tier 2a method is highly uncertain, inventory compilers are strongly encouraged to apportion gas consumption by process type and to use the Tier 2c method, a hybrid Tier 2c / Tier 3a method, or ultimately a full Tier 3a method. If apportioning gas usage proves problematic for a particular facility, the Tier 3b method could be an alternate approach providing higher accuracy without the need to develop a complex apportioning model for the facility.

EQUATION 6.10 (NEW)
ESTIMATE OF THE MASS FRACTION OF GAS I EXHAUSTED FROM PROCESS TOOLS EQUIPPED WITH EMISSION CONTROL TECHNOLOGIES

$$a_i = \frac{\sum_p \gamma_{i,p} \bullet n_{i,p,a} + m_{i,q,a}}{\sum_p \gamma_{i,p} \bullet n_{i,p} + m_{i,q}}$$

Where:

a_i = estimate of the fraction of gas i exhausted from process tools equipped with suitable emissions control technologies, site-specific fraction

$n_{i,p,a}$ = number of tools that use gas i, that run process type p, and that are equipped with suitable emissions control technologies for gas i, site-specific

$m_{i,q,a}$ = number of tools that use gas i, that run process type q, and that are equipped with suitable emissions control technologies for gas i, site-specific

$n_{i,p}$ = total number of tools using gas i and running process type p, site-specific

$m_{i,q}$ = total number of tools using gas i and running process type q, site-specific

$\gamma_{i,p}$ = default factor reflecting the ratio of uncontrolled emissions per tool of input gas i from tools running process type p to uncontrolled emissions per tool of input gas i from process tools running process type q, fraction

i = input gas

p = weighted process type. When Equation 6.10 is being used for the Tier 2a or Tier 2b method, p includes IPC and/or ITC. When Equation 6.10 is being used for the Tier 3b method and gas i is an FC, p includes RPC, IPC, and/or ITC. When Equation 6.10 is being used for the Tier 3b method and gas i is N_2O, p consists of thin-film deposition.

Q = reference process type. When gas i is an FC, q consists of the combination of etching and/or wafer-cleaning processes. When gas i is N_2O, q consists of the "Other" process type.

EQUATION 6.11 (NEW)
ESTIMATE OF THE MASS FRACTION OF BY-PRODUCT K EXHAUSTED FROM PROCESS TOOLS EQUIPPED WITH EMISSION CONTROL TECHNOLOGIES

$$a_{k,i} = \frac{\sum_p \gamma_{k,i,p} \bullet n_{k,i,p,a} + m_{k,i,q,a}}{\sum_p \gamma_{k,i,p} \bullet n_{k,i,p} + m_{k,i,q}}$$

Where:

$a_{k,i}$ = estimate of the fraction of by-product k formed from input gas i that is exhausted from process tools that are equipped with suitable emissions control technologies, site-specific fraction

$n_{k,i,p,a}$ = number of tools that exhaust by-product k formed from input gas i, that run process type p, and that are equipped with suitable emissions control technology for by-product k, site-specific

$m_{k,i,q,a}$ = number of tools that exhaust by-product k formed from input gas i, that run process type q, and that are equipped with suitable emissions control technology for by-product k, site-specific

$n_{k,i,p}$ = total number of tools exhausting by-product k formed from input gas i and running process type p, site-specific

$m_{k,i,q}$ = total number of tools exhausting by-product k formed from input gas i and running process type q, site-specific

$\gamma_{k,i,p}$ = default factor reflecting the ratio of uncontrolled emissions per tool of by-product k from process tools using gas i and running process type p to uncontrolled emissions per tool of by-product k from process tools using gas i and running process type q, fraction

i = input gas

k = by-product gas

p = weighted process type. When Equation 6.11 is being used for the Tier 2a or Tier 2b method, p includes IPC and/or ITC. When Equation 6.11 is being used for the Tier 3b method and gas i is an FC, p includes RPC, IPC, and/or ITC. When Equation 6.11 is being used for the Tier 3b method and gas i is N_2O, p consists of thin-film deposition.

Q = reference process type. When gas i is an FC, q consists of the combination of etching and/or wafer-cleaning processes. When gas i is N_2O, q consists of the "Other" process type.

Finally, inventory compilers should calculate, for each reporting site, the average uptime of all emissions control systems connected to process tools (UT), using Equation 6.12. To this end, inventory compilers should account for the total time (Td_n) that any emissions control system n connected to process tool(s) in the reporting facility is not in operational mode when at least one of the manufacturing tools connected to emissions control system n is in operation, and the total time (TT_n) in which emissions control system n has at least one associated manufacturing tool in operation. For determining the amount of tool operating time, inventory compilers 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, inventory compilers should prorate the operating time to account for the days in which the tool was not installed and treat any partial day that a tool was installed as a full day (1,440 minutes) of tool operation. For an emissions control 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. For tools that are idle with no gas flowed through the tool for part of the year, inventory compilers may calculate total tool time using the actual time that gas is flowing through the tool. Inventory compilers should also note that UT may be set to one (1) if suitable backup emissions control equipment or interlocking with the process tool is implemented for each emissions control system. Thus, using interlocked process tools or backup emissions control systems reduces uncertainty by eliminating the need to estimate UT for the reporting facility.

EQUATION 6.12 (NEW)
UPTIME OF EMISSIONS CONTROL SYSTEMS

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

Where:

UT = Average uptime factor of all emissions control systems connected to process tools, fraction.

Td_n = Total time that emissions control 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 emissions control system n is in operation, minutes per year.

TT_n = Total time during which emissions control system n has at least one associated manufacturing tool in operation, minutes per year.

n = emissions control system.

Tier 2b method

The Tier 2b method is applicable to the semiconductor sub-sector and to MEMS manufacturing that uses tools and processes similar to those used to manufacture semiconductors (for further details see discussion in the Choice of method section, in particular footnote 3). As discussed in section 6.2.1, the Tier 2b method is preferred over the Tier 2a method unless it is not possible to distinguish gas consumption by wafer size (e.g., for semiconductor manufacturing facilities that process multiple wafer sizes and cannot apportion gas consumption between them). The Tier 2b method uses the same set of equations as the Tier 2a method (Equations 6.5 to 6.12), but distinct U_i, $B_{k,i}$, $\gamma_{i,p}$, and $\gamma_{k,i,p}$ default factors are provided by the wafer size being manufactured (≤200 mm vs. 300 mm, see Tables 6.8 and 6.9). With this distinction in mind, all other site-specific Tier 2b factors (which are the same as for the Tier 2a method)-are estimated in the same manner as for the Tier 2a method. Thus, inventory compilers using the Tier 2b method should have direct communication with industry to gather consumption and emissions control-related data and verify that emissions control technologies for which reductions are being claimed are installed and used in accordance with the guidance provided in section 6.2.2.1.

Total Tier 2b emissions are calculated using Equations 6.5, 6.6, and 6.7 and are equal to the sum of emissions from all unreacted gases i used in the production process (E_i), plus emissions of all by-products k (BPE_k) resulting from the conversion of all input gases i used during production, plus emissions of CF_4 from hydrocarbon-fuel-based combustion emissions control systems ($EAB_{i,CF4}$). As in the Tier 2a method, $EAB_{i,CF4}$ may be set to zero if the emissions control equipment manufacturer can certify that reactions between hydrocarbon fuel and F_2 to form CF_4 is not occurring within their emissions control system (i.e. certify that $AB_{i,CF4} = 0$).

Tier 2c method

The Tier 2c method is applicable to the semiconductor, display, and PV sub-sectors, and to MEMS manufacturing that is carried out using tools and processes similar to those used to manufacture semiconductors (for further details see discussion in the Choice of method section, in particular footnote 3). The Tier 2c method is based on a set of equations that account for default emission factors that are provided for distinct process types p ($U_{i,p}$ and $B_{k,i,p}$). In the Tier 2c method for the semiconductor sub-sector, there are six process types p defined as 1) etching and wafer cleaning (EWC), 2) remote plasma cleaning (RPC), 3) in-situ plasma cleaning (IPC), 4) in-situ thermal cleaning (ITC), 5) N_2O TFD, and 6) N_2O 'Other'. In the Tier 2c method for the display sub-sector there are only 4 process types p defined as 1) etching, 2) remote plasma cleaning (RPC), 3) in-situ plasma cleaning (IPC), and 4) N_2O TFD. In the case of the Tier 2c method for the PV subsector, process types are defined as 1) etch and 2) TFD chamber cleaning. In addition, the Tier 2c method provides distinct emission factors for different substrate sizes for the semiconductor sub-sector (≤200 mm and 300 mm), but the Tier 2c method does not distinguish emission factors for different substrate size for the display sub-sector (the same Tier 2c default emissions factors are applicable to display manufacturing tools for generations 4, 5, 6, 7, etc.) and the PV sub-sector.

The $U_{i,p}$ and $B_{k,i,p}$ default emission factors for the Tier 2c method are included in Tables 6.10 to 6.11 for the semiconductor sub-sector (≤200 mm and 300 mm substrate sizes respectively), Table 6.12 for the display sub-sector, and Table 6.13 for the PV sub-sector. The other default emission factors used for the Tier 2c method are the destruction removal efficiencies (DRE) of gases i and by-products k (d_i, d_k - see Table 6.17), which are assumed to be the same across all sub-sectors and across all Tier 2 methods. The Tier 2c method also uses site-specific factors ($C_{i,p}$, $D_{i,p}$, $D_{k,i,p}$, $a_{i,p}$, $a_{k,i,p}$, $n_{i,p,a}$, $n_{i,p}$, $n_{k,i,p,a}$, $n_{k,i,p}$, UT_p, $Td_{n,p}$, $TT_{n,p}$), and inventory compilers using the Tier 2c method should directly communicate with industry to gather consumption and emissions control-related data and to ensure that reductions are not attributed to emissions control devices unless the devices are installed and used in accordance with the guidance provided in section 6.2.2.1. Inventory compilers should note that the consumption of gas i ($C_{i,p}$) takes into account the heel factor ($h_{i,l}$), 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 (see Section on Gas Consumption and Apportioning).

As discussed in section 6.2.1, the use of the Tier 2c method is preferred over the Tier 2a or Tier 2b methods in the semiconductor sub-sector because the Tier 2c default emission factors are expected to be more accurate than the Tier 2b or 2a factors. However, using the Tier 2c method requires apportioning gas consumption for all gases and process types, which introduces additional complexity. Please see the section on Gas Consumption and Apportioning for further detail.

Tier 2c 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, plus emissions of CF_4 from hydrocarbon-fuel-based combustion emissions control systems ($EAB_{i,CF4}$, which may be set to zero if the emissions control equipment manufacturer can certify that reactions between hydrocarbon fuel and F_2 to form CF_4 is not occurring within their emissions control systems). Tier 2c emissions are calculated using process-type-dependent Equations 6.13 to 6.20.

EQUATION 6.13 (UPDATED)
EMISSION OF INPUT GAS I

$$E_i = \sum_p [C_{i,p} \bullet (1 - U_{i,p}) \bullet (1 - D_{i,p})]$$

Where:

E_i = emissions of unreacted input gas, kg

$C_{i,p}$ = consumption of input gas i for process type p, kg

$U_{i,p}$ = use rate of gas i for process p, fraction destroyed or transformed in process p

$D_{i,p}$ = overall reduction of mass of gas i emitted from process type p, site-specific fraction calculated per Equation 6.16

i = input gas

p = process type

EQUATION 6.14 (UPDATED)
PROCESS BY-PRODUCT EMISSIONS FROM INPUT GAS I

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

Where:

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

$B_{k,i,p}$ = emission factor for by-product k generated from use of input gas i in process type p, kg of by-product k created per kg of gas i consumed for process type p

$C_{i,p}$ = consumption of input gas i for process type p, kg

$D_{k,i,p}$ = overall reduction of mass of gas k by-product emissions from use of input gas i in process type p, site-specific fraction calculated per Equation 6.17

i = input gas

k = by-product gas

p = process type

When neither the gases used nor the films etched or cleaned contain carbon, the $B_{k,i,p}$ factors may be equated to zero in Equation 6.14. When both carbon-containing and non-carbon-containing films are included in the film stacks forming final electronic devices, 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 $B_{k.i,p}$ 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. (See Box 6.2 and the discussion under Equation 6.6 for more on this issue.)

When NF_3 is used in RPC processes or F_2 is used as an input gas and when hydrocarbon-fuel-based combustion emissions control technology is used, direct reaction with hydrocarbon fuel and F_2 (including F_2 resulting from the decomposition of NF_3 in RPC processes) to form CF_4 can occur. Unless the emissions control equipment original equipment manufacturer (OEM) or electronics manufacturer can certify that the rate of conversion from F_2 to CF_4 or from NF_3 to CF_4 is <0.1 percent on a mass basis, Equation 6.15 should be used to estimate the amount of CF_4 produced within and emitted from the emissions control device.

EQUATION 6.15 (NEW)
BY-PRODUCT EMISSIONS FROM HYDROCARBON-FUELLED COMBUSTION EMISSIONS CONTROL SYSTEMS

$$EAB_{i,CF_4} = \sum_p C_{i,p} \bullet (1 - U_{i,p}) \bullet (1 - \eta_p) \bullet AB_{i,CF_4}$$

Where:

i = input gas (i = only NF_3 used in RPC processes or F_2 for the purpose of Equation 6.15)

$EAB_{i,CF4}$ = emissions of CF_4 from hydrocarbon-fuel-based combustion emissions control systems when direct reaction with hydrocarbon fuel and fluorinated species is not certified not to occur by the emissions control equipment OEM or electronics manufacturer, kg

$C_{i,p}$ = consumption of input gas i for process type p (i = only NF_3 used in RPC processes or F_2 for the purpose of Equation 6.15), kg

$U_{i,p}$ = use rate of gas i for process p, fraction destroyed or transformed in process p

η_p = ratio of emissions control systems connected to tools running process type p and certified not to form CF_4 within emissions control systems to the total number of all emissions control systems, site-specific fraction

$AB_{i,CF4}$ (i = only NF_3 used in RPC processes or F_2 for the purpose of Equation 6.15)

= mass fraction of NF_3 used in RPC processes or F_2 in process exhaust gas that is converted into CF_4 by direct reaction with hydrocarbon fuel and F_2 gas in a combustion emissions control system. $AB_{i,CF4}$ is set to zero if the emissions control equipment OEM or electronics manufacturer can certify that the rate of conversion from F_2 to CF_4 or from NF_3 to CF_4 is <0.1 percent; otherwise, a default value of $AB_{NF3,CF4} = 0.093$ or $AB_{F2,CF4} = 0.116$ should be used.

p = process type (RPC using NF_3 or any process type using F_2 for the purpose of Equation 6.15)

Inventory compilers should calculate the overall reductions in emissions of process gas i and by-product k ($D_{i,p}$, $D_{k,i,p}$) based on site-specific information using Equations 6.16 and 6.17, factoring in the mass fraction of gas i and by-product k exhausted from process tools running process type p and equipped with suitable emissions control technologies ($a_{i,p}$, $a_{k,i,p}$), the destruction removal efficiency of gas i and by-product k (d_i, d_k), and the average uptime of emissions control systems connected to process tools running process type p (UT_p).

EQUATION 6.16 (NEW)
EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL EQUIPMENT ON INPUT GAS I

$$D_{i.p} = a_{i,p} \bullet d_i \bullet UT_p$$

Where:

$D_{i,p}$ = overall reduction of mass of gas i emitted from process type p, fraction

$a_{i,p}$ = estimate of the fraction of gas i exhausted from process tools running process type p and equipped with suitable emissions control technologies, site-specific fraction calculated using Equation 6.18

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

UT_p = average uptime factor of all emissions control systems connected to tools running process type p, site-specific fraction calculated per Equation 6.20

i = input gas

k = by-product gas

p = process type

EQUATION 6.17 (NEW)
EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL EQUIPMENT ON BY-PRODUCT K

$$D_{k,i,p} = a_{k,i,p} \bullet d_k \bullet UT_p$$

Where:

$D_{k,i,p}$ = overall reduction of mass of gas k by-product emitted from use of input gas i in process type p, site-specific fraction

$a_{k,i,p}$ = estimate of the fraction of by-product k exhausted from process tools using input gas i in process type p and equipped with suitable emissions control technologies, site-specific fraction calculated using Equation 6.19

d_k = Destruction Removal Efficiency (DRE) for by-product k, fraction

UT_p = average uptime of all emissions control systems connected to tools running process type p, site-specific fraction calculated per Equation 6.20

i = input gas

k = by-product gas

p = process type

The use of gamma weighting factors is not required in the Tier 2c method because uncontrolled emissions from different process types are accounted for separately through gas consumption allocation. Instead, to estimate the site-specific $a_{i,p}$ value, inventory compilers may calculate the ratio of the number of tools running process type p (emitting gas i) that are equipped with suitable emissions control technologies ($n_{i,p,a}$) to the total number of tools running process type p and emitting gas i, using Equation 6.18."Suitable" means that an emissions control technology is capable of abating a particular gas to a minimum destruction removal efficiency in a site-specific worst-case scenario (please see Section 6.2.2.1 on Emissions Control Technology Factors for more details). Note that inventory compilers may obtain more refined estimates of $a_{i,p}$ by counting the number of process chambers running process type p (emitting gas i) that are connected to suitable emissions control technologies, or by using other site-specific approaches that may be more accurate.

EQUATION 6.18 (NEW)
ESTIMATE OF THE FRACTION OF MASS OF GAS I EMITTED FROM PROCESS P FROM TOOLS EQUIPPED WITH EMISSIONS CONTROL EQUIPMENT

$$a_{i,p} = \frac{n_{i,p,a}}{n_{i,p}}$$

Where:

$a_{i,p}$ = estimate of the fraction of gas i exhausted from process tools running process type p and equipped with suitable emissions control technologies, site-specific fraction

$n_{i,p,a}$ = number of process tools running process type p (emitting gas i) that are equipped with suitable emissions control technologies, site-specific

$n_{i,p}$ = total number of process tools running process type p and emitting gas i, site-specific

i = input gas

p = process type

To estimate the site-specific $a_{k,i,p}$ value, use Equation 6.19 calculate the ratio of the number of tools that run process type p, emit by-product k from use of input gas i, and are equipped with suitable emissions control technologies ($n_{k,i,p,a}$) to the total number of tools that run process type p and emit by-product k from use of input gas i ($n_{k,i,p}$). Note also that inventory compilers may obtain more refined estimates of $a_{k,i,p}$ by counting the number of process chambers that run process type p, emit by-product k from use of input gas i, and are connected to suitable emissions control technologies, or by using other site-specific approaches that may be more accurate.

EQUATION 6.19 (NEW)
ESTIMATE OF THE FRACTION OF MASS OF BY-PRODUCT K EXHAUSTED FROM USE OF INPUT GAS I IN PROCESS P FROM TOOLS EQUIPPED WITH EMISSIONS CONTROL EQUIPMENT

$$a_{k,i,p} = \frac{n_{k,i,p,a}}{n_{k.i.p}}$$

Where:

$a_{k,i,p}$ = estimate of the fraction of by-product k exhausted from process tools running process type p and equipped with suitable emissions control technologies, site-specific fraction

$n_{k,i,p,a}$ = number of process tools that run process type p, emit by-product k from use of input gas i, and are equipped with suitable emissions control technologies, site-specific

$n_{k,i,p}$ = total number of process tools running process type p and emitting by-product k from use of input gas i, site-specific

i = input gas

k = by-product gas

p = process type

Finally, inventory compilers should calculate, for each reporting site, the average uptime of all emissions control systems connected to process tools running process type p (UT_p), using Equation 6.20. To this end, inventory compilers should account for the total time ($Td_{n,p}$) that any emissions control system n connected to process tool(s) running process type p in the reporting facility is not in operational mode when at least one of the manufacturing tools connected to emissions control system n is in operation, and the total time ($TT_{n,p}$) in which emissions control system n has at least one associated manufacturing tool in operation. For determining the amount of tool operating time, inventory compilers 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, inventory compilers should prorate the operating time to account for the days in which the tool was not installed and treat any partial day that a tool was installed as a full day (1,440 minutes) of tool operation. For an emissions control 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. For tools that are idle with no gas flowed through the tool for part of the year, inventory compilers may calculate total tool time using the actual time that gas is flowing through the tool. Inventory compilers should also note that UT_p may be set to one (1) if suitable backup emissions control equipment or interlocking with the process tool is implemented for each emissions control system. Thus, using interlocked process tools or backup emissions control systems reduces uncertainty by eliminating the need to estimate UT for the reporting facility.

EQUATION 6.20 (NEW)
UPTIME OF EMISSIONS CONTROL SYSTEMS

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

Where:

UT_p = average uptime of all emissions control systems connected to process tools running process type p, site-specific fraction

$Td_{n,p}$ = total time that emissions control system n connected to process tools running process type p in the facility is not in operational mode when at least one of the manufacturing tools connected to emissions control system n is in operation, minutes per year

$TT_{n,p}$ = total time during which emissions control system n has at least one associated manufacturing tool running process type p in operation, minutes per year

n = emissions control 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 type (e.g. Si, SiC, or glass) and size (e.g., moving to 450 mm wafers in semiconductor manufacturing);

- Use of a new gas in an existing process type (i.e. in-situ plasma cleaning, remote plasma cleaning, or in-situ thermal cleaning; etching; 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;
- Use of new input process GHGs, use of new combinations of process greenhouse gases, or use of low- or no-GWP materials that have the potential to form GHG by-products.

If default emission factors are not available under Tier 2 (e.g., a new gas or process type is introduced), facilities can estimate emissions using Tier 2 and assume a default emission factor (1-U) = 0.8 with by-product emission factors of 0.15 for CF_4 and 0.05 for C_2F_6.[10] Alternatively, facilities can undertake process emissions characterization under Tier 3a and use a hybrid method. 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. It is *good practice* to undertake process emissions characterization and use a hybrid method when the new gas and process type combination accounts for 1 percent or more of facility GHG consumption by mass and results in estimated emissions of more than 500 $mtCO_2e$, based on the 0.8, 0.15, and 0.05 default emission factors above.

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. Any country-specific default emission factors should represent the full range of processes in the country for each process type, including not only the emission factors for the new or changed processes, but also emission factors for previously existing processes that are still used. Most countries are likely to find it challenging to develop robust, representative country-specific emission factors, and technological changes in a particular country are likely to quickly diffuse into other countries. Thus, it is generally preferable to refine default emission factors at the global rather than at the country level. In this context, facilities are encouraged to report measured emission factors to the IPCC Emission Factor Database (EFDB) in a transparent manner through a process allowing protection of any underlying confidential information.

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 type or 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, 300 mm 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 percent of total gas used in year 2; 25 percent in year 3; 10 percent in year 4; and 0 percent 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.

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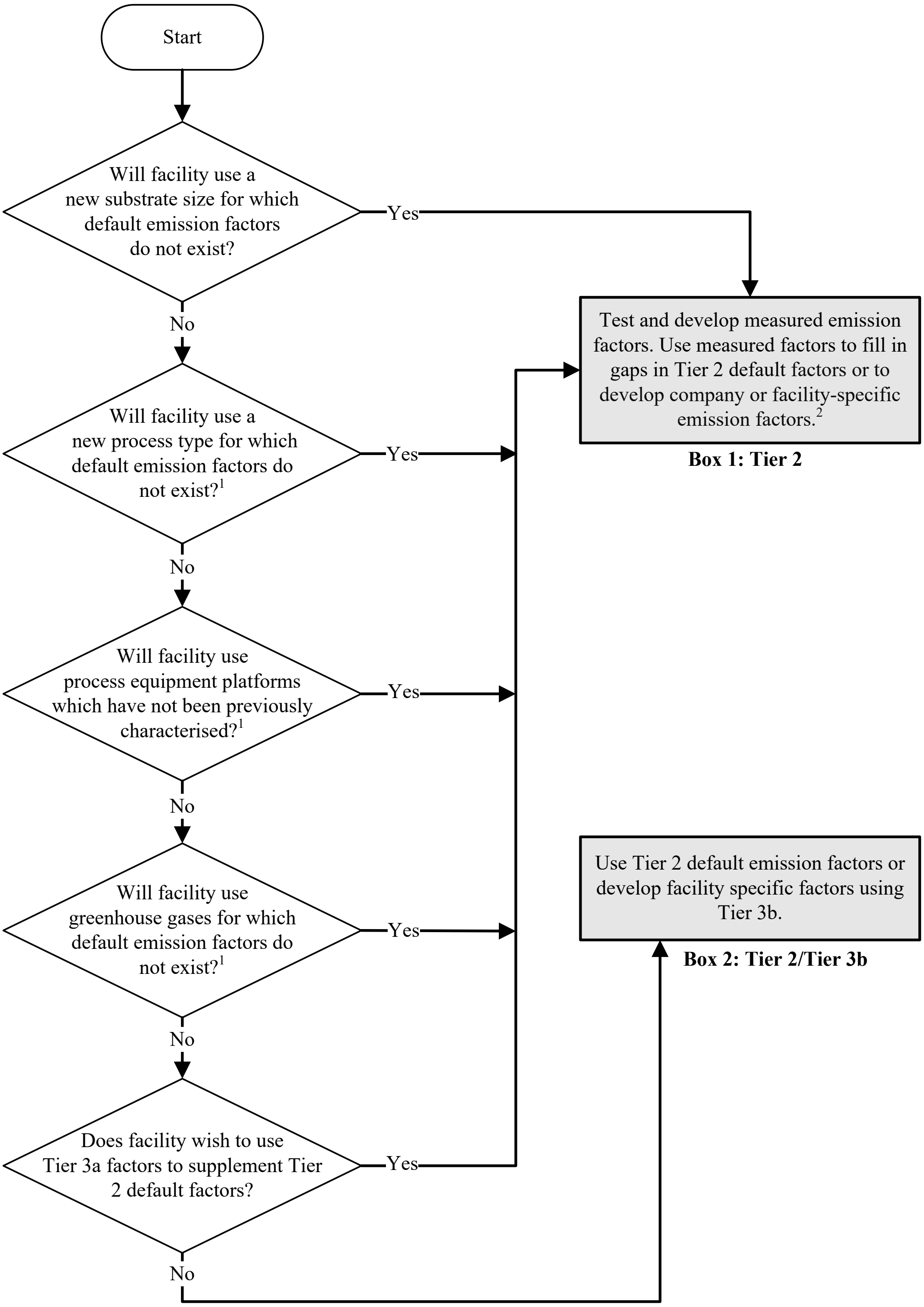
[10] These defaults assume that all of the input gas is either emitted or converted into CF_4 or C_2F_6. In the majority of cases where emission factor data are available, both CF_4 and C_2F_6 are emitted as by-products. The default (1-U) is conservatively based on the least efficient (1-U) for etch or wafer cleaning processes (0.8 for C_2F_6 in Table 6.10). Due to a generally higher CF_4 by-product emission factor for most input gas/process combinations, the majority (75 percent) of the remaining mass is assigned to CF_4 and the rest to C_2F_6.

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



Note:

1. If a new gas and process combination are used that accounts for less than 1 percent of facility fluorinated GHG consumption by mass and (1-U) is not measured or not listed, compiler may assume (1-U) = 0.8, B_{CF4} = 0.15, B_{C2F6} = 0.05.

2. Mechanism to submit Tier 3a data to EFDB is still to be designed at the time of writing of this *2019 Refinement*.

TIER 3 METHODS – SITE-SPECIFIC PARAMETERS

Tier 3a – Measured process-specific parameters

The Tier 3a method can be applied to all sub-sectors covered in Chapter 6 (semiconductor, display, PV and MEMS) and uses the same set of equations as the Tier 2c method; however, Tier 3a uses measured values for parameters in Equations 6.13 to 6.20 (see Table 6.3 for details). As discussed earlier, 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 facility. For example, a facility may have abatement efficiencies that are different from the default DRE values for emission control systems installed on a certain subset of process tools, or may account for emissions from a particular recipe or technology that is more efficient or that may have been developed for the purpose of reducing emissions. Note that in the case of a comprehensive technology change, such as the adoption of a new substrate size (e.g., 450 mm in semiconductor industry), the Tier 3a method would be broadly applied.

For the Tier 3a method, the $(1-U_{i,p})$ and $B_{k,i,p}$ emission factors in Equations 6.13 to 6.15 and 6.18 to 6.19 are measured for recipes or for families of similar recipes. Thus, the main distinction between the Tier 3a method and the Tier 2c method is that, for the Tier 3a method, p in Equations 6.13 to 6.20 is to be interpreted as meaning a 'recipe' or a family of similar recipes. A recipe can be defined as a specific combination of process conditions (input gas type and flows, plasma power, pressure, temperature, duration, etc.) and technologies used to etch patterns onto electronics devices, to clean film deposition chambers, or to deposit films on substrates. A centreline recipe can be used to establish Tier 3a emission factors for a recipe and each family of similar recipes. Recipes are deemed 'similar' when the centreline process can reasonably be deemed representative of facility-specific process conditions despite potential variability of such process conditions around the centreline process during normal manufacturing operations, and when the substrate size, process type, tool platform and process chamber, film type (SiO_x, SiO_xN_y, Si_xN_y, W, etc.), and input process gas(es) 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 emissions control systems that may be used in a particular electronics manufacturing facility. For this reason, it is *good practice* for facilities 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 the top 75 percent of total process greenhouse gas usage in kg and the top 50 percent of emissions in kg CO_2e.).
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 3a measurements are made, the reporting facility should document the following:

- Date measurements were made;
- Industry sub-sector;
- Substrate size;
- Process type;
- Film type;
- Tool manufacturer, platform and model/chamber name;
- Input gases;
- Process conditions (gas flows, pressure, temperature, power, duration, etc.);
- Input gas emission factors;
- By-product emission factors;
- Fluorine mass balance closure;
- Measurement protocol used.

In addition, facilities using the 3a approach should document all facility-specific process emission factors or emissions control equipment DREs that have been measured by the reporting facility, 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 emissions control technology or emissions control 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 3b method—Stack testing

The Tier 3b method may be applied to all sub-sectors covered in Chapter 6 (semiconductor, display, PV and MEMS). Stack testing measures the amount of greenhouse gases emitted from a specific facility through stack systems. A stack system is considered to be one or more stacks that are connected by a common header or manifold, through which an FC- or N_2O-containing gas stream originating from one or more processes is, or has the potential to be, released to the atmosphere. Stack testing is a method commonly used by electronic devices manufacturing facilities to quantify emissions and demonstrate compliance for regulated pollutants used in manufacturing, such as acid gases (e.g., hydrogen fluoride, hydrogen chloride, fluorine, nitric acid, ammonia) and volatile organic compounds (VOCs). The individual process chamber operations that use 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 greenhouse gas emissions from facility stack systems 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 system for in-situ analysis. 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 site-specific emission factors. The stack method may not be appropriate for facilities with many stacks, frequent changes in production technology or product mix, or an inability to track gas use during testing or emissions control equipment uptime during testing. It is important to perform stack testing when production levels in the fab are representative of year-round production, and when emissions control system uptime is representative of year-round uptime.

Testing Frequency

It is *good practice* for reporting facilities to test all stack systems at the reporting facility that have the potential to emit greenhouse gases in the first year of testing. Typically, this means all acid and caustic/alkali stack systems at the facility should be tested because these are generally the stack systems connected to processes using FC compounds in a fab. It is also important to test all stacks on relevant stack systems during the first year of testing to determine that there are negligible differences in flow or concentration between these stacks. If a facility 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. In subsequent years, reporting facilities may consider less frequent testing for stack systems that comprise less than 10 percent of total process GHG emissions (expressed in CO_2e). On the other hand, facilities 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 facilities, 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) If annual consumption, in terms of CO_2e, for any individual FC gas compared with the total of all FC gases changes by more than 10 percentage points from the most recent emissions test. For example, if the use of a single gas converted to CO_2e goes from 25 percent of total gas consumption to greater than 35 percent of total gas consumption, a retest would be triggered for the subsequent year.

(ii) Annual consumption of an FC that was not used during the emissions test and that is not included in the facility-specific emission factors rises to 5 percent (expressed in CO_2e) of the annual FC consumption of the fab. (For FCs that were not used during the emissions test and whose consumption falls below 5% of annual fab consumption, Tier 2 or 3a methods should be used to estimate emissions to ensure completeness.)

(iii) A change by more than 20 percent in the fraction of process tools equipped with emissions control systems, compared to the fraction during the most recent emissions test.

(iv) A change in the substrate size used by the facility since the most recent emissions test.

Stack test method

For each stack system in the reporting facility for which testing is required, inventory compilers should measure the emissions of each FC gas and N_2O from the stack system by conducting an emission test using the methods mentioned in Table 6.14, or their equivalents. In addition, inventory compilers should measure the facility-specific emissions and consumption of each FC and N_2O according to the following steps:

- 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. The analytical method should be validated using US EPA Method 320 or an equivalent validation method.
- Emissions testing should be conducted during a period of 8 hours or longer per stack system while the facility is operating at a representative level with representative emissions control system uptime. (Representative uptime is particularly important for emission control systems that have not been certified not to form CF_4 from F_2 exhausted by the process.) Representative in this case means that normal process tools' or emissions control systems' maintenance is being performed during the stack emissions test and that processes running during the test are indicative of normal facility operations.
- Measurements should be taken for N_2O and all FC gases known to be used by the facility and any possible FC gas by-products. It is recommended measurements be taken for CF_4, C_2F_6, C_3F_8, C_4F_8, C_5F_8, CHF_3, CH_2F_2, and CH_3F as these gases may be formed as by-products.
- The amount of each FC and N_2O gas consumed by each facility during the sampling period should be determined. Where starting and ending gas container pressures are used to estimate consumption, appropriate adjustments for temperature and deviations from ideal gas law behaviour should be made (e.g., by applying the Redlich, Kwong, Soave equation of state with appropriate values for each FC gas and N_2O). Because stack testing is conducted over a relatively brief period, measurements and calculations of gas consumption during that period should be precise to ensure that the resulting emission factors are accurate.
- If consumption of an FC gas is too low to be accurately measured during the testing period, then in order to account for usage, either the testing period should be increased or consumption should be calculated for the testing period by pro-rating long-term consumption data.

Inventory compilers should calculate the emissions of each FC gas and N_2O consumed as an input gas using Equation 6.21 and each FC gas formed as a by-product using Equation 6.22. If a stack system is comprised of multiple stacks, inventory compilers should sum the emissions from each stack in the stack system when using Equation 6.21 or Equation 6.22.

EQUATION 6.21 (NEW)
TOTAL GHG INPUT GAS EMITTED FROM STACK SYSTEM DURING SAMPLING PERIOD

$$ES_{i,s} = MW_i \bullet Q_s \bullet \frac{1}{SV} \bullet \frac{1}{10^3} \bullet \sum_{m=1}^{N} \frac{X_{i,s,m}}{10^9} \bullet \Delta t_m$$

Where:

$ES_{i,s}$ = emissions of input gas i from stack system s during the sampling period, kg

MW_i = molecular weight of gas i , g/g-mole

Q_s = flow rate of stack system s during the sampling period, m^3/min.

SV = standard molar volume of gas, 0.0240 m^3/g-mole at 68°F and 1 atm.

$X_{i,s,m}$ = average concentration of input gas i in stack system s during time interval m, ppbv

Δt_m = length of time interval m in the FTIR sampling period, 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 = input gas

s = stack system

N = total number of time intervals m in sampling period

m = time interval

EQUATION 6.22 (NEW)

TOTAL FC BY-PRODUCT EMITTED FROM STACK SYSTEM DURING SAMPLING PERIOD

$$ES_{k,s} = MW_k \bullet Q_s \bullet \frac{1}{SV} \bullet \frac{1}{10^3} \bullet \sum_{m=1}^{N} \frac{X_{k,s,m}}{10^9} \bullet \Delta t_m$$

Where:

$ES_{k,s}$ = emissions of by-product k emitted from stack system s during the sampling period, kg

MW_k = molecular weight of by-product gas k, g/g-mole

Q_s = flow rate of stack system s during the sampling period, m 3/min

SV = standard molar volume of gas, 0.0240 m 3/g-mole at 68 °F and 1 atm.

$X_{k,s,m}$ = average concentration of by-product k in stack system s during time interval m, ppbv

Δtm = length of time interval m in the FTIR sampling period, 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

k = by-product gas

s = stack system

N = total number of time intervals m in sampling period

m = time interval

When calculating emissions, inventory compilers should use the following guidance and the accompanying requirements of recognized maximum field detection limits (FDLs) as detailed in Table 6.15. Field detection limits for instrumentation used in stack testing should not exceed those depicted in Table 6.15

a. If an FC gas or N_2O is consumed during the sampling period, but its emissions are not detected, the ½ FDL value determined for the target compound should be used for the value of $X_{i,s,m}$ in Equation 6.21 .

b. If an FC gas or N_2O is consumed during the sampling period but only detected intermittently during the sampling period, the detected concentration should be used for the value of $X_{i,s,m}$ in Equation 6.21 when available, and a concentration corresponding to one-half of the FDL determined for the target compound should be used for the value of $X_{i,s,m}$ when the target compound is not detected.

c. If an FC gas is not consumed during the sampling period, is not detected during the sampling period, but is an expected by-product, a concentration corresponding to one-half of the FDL determined for the target compound should be used for the value of $X_{k,s,m}$ in Equation 6.22. Expected by-products are CF_4, C_2F_6, CHF_3, CH_2F_2, and CHF_3.

d. If an FC gas or N_2O is not consumed during the sampling period, is not detected during the sampling period, and is not an expected by-product listed in c above, then inventory compilers may assume that emissions for the target compound for the tested stack system are zero.

After calculating $ES_{i,s}$ and $ES_{k,s}$, inventory compilers should calculate a facility-specific emission factor for each input gas consumed (in kg of FC gas or N_2O emitted per kg of input gas i consumed) in the tools that vent to stack systems that are tested, as applicable. For FC gases, use Equations 6.23a and 6.23b or 6.23a and 6.23c of this section. For N_2O, always use Equation 6.23b, even if this results in an emission factor greater than 1.

Equation 6.23a calculates $ES_{imax,f}$, the controlled emissions that would result during the sampling period if the utilization rate for the FC input gas i were equal to 0.2 (the minimum discussed above in “Adapting Tier 2 Methods to Account for Technological Changes”). If $\sum_s ES_{i,s}$ (the total measured emissions of the FC across all stack systems) falls below $ES_{imax,f}$, then use Equation 6.23b to calculate $EF_{i,f}$ (the abated 1-U factor for the FC input gas i). If $\sum_s ES_{i,s}$ equals or exceeds $ES_{imax,f}$, use Equation 6.23c to calculate $EF_{i,f}$, and treat the difference between $\sum_s ES_{i,s}$ and $ES_{imax,f}$ as a by-product of the other input gases, using Equation 6.24 of this section.

EQUATION 6.23A (NEW)
MAXIMUM CONTROLLED EMISSIONS OF FCI FROM ITS USE AS INPUT GAS

$$ES_{i\max,f} = 0.8 \bullet Activity_{i,f} \bullet [1-(a_{i,f} \bullet UT_f \bullet d_i)]$$

Where:

$ES_{imax,f}$ = maximum expected controlled emissions of FC_i from the fab from its use as an input gas during the sampling period, kg

$Activity_{i,f}$ = consumption of FC input gas i for facility f during the sampling period, kg

UT_f = total uptime of all emissions control systems for facility f during the sampling period, site-specific fraction as calculated in Equation 6.27

$a_{i,f}$ = estimate of the fraction of FC input gas i exhausted from process tools equipped with suitable emissions control technologies for facility f, site-specific fraction as determined in Equation 6.10

d_i = Destruction Removal Efficiency (DRE) for FC input gas i, fraction

i = FC input gas

f = facility

EQUATION 6.23B (NEW)
GAS SPECIFIC EMISSION FACTOR FOR INPUT GAS

$$EF_{i,f} = \frac{\sum_s ES_{i,s}}{Activity_{i,f} \bullet (UT_f + \frac{1-UT_f}{1-(a_{i,f} \bullet d_i)})}$$

Where:

$EF_{i,f}$ = emission factor for input gas i and facility f representing 100 percent emissions control system uptime, kg emitted per kg of input gas consumed

$ES_{i,s}$ = emissions of input gas i from stack system s during the sampling period, kg

$Activity_{i,f}$ = consumption of input gas i for facility f during the sampling period, kg

UT_f = total uptime of all emissions control systems for facility f during the sampling period, as calculated in Equation 6.27, site-specific fraction

$a_{i,f}$ = estimate of the fraction of gas i exhausted from process tools equipped with suitable emissions control technologies for facility f, site-specific fraction as determined in Equation 6.10

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

i = input gas

s = stack system

f = facility

EQUATION 6.23C (NEW)
MAXIMUM CONTROLLED GAS-SPECIFIC EMISSION FACTOR FOR INPUT GAS FCI

$$EF_{i,f} = 0.8 \bullet [1-(a_{i,f} \bullet d_i)]$$

Where:

$EF_{i,f}$ = emission factor for FC input gas i and facility f representing a 20-percent utilization rate and 100-percent emissions control system uptime, kg emitted per kg of input gas consumed

$a_{i,f}$ = estimate of the fraction of FC input gas i exhausted from process tools equipped with suitable emissions control technologies for facility f, site-specific fraction as determined in Equation 6.10

d_i = Destruction Removal Efficiency (DRE) for FC input gas i, fraction

i = FC input gas

f = facility

After calculating $EF_{i,f}$, inventory compilers should calculate a facility-specific emission factor for each FC by-product k (in kg of by-product k per kg of total FC input gases i consumed) in the tools vented to stack systems that are tested, as applicable, using Equation 6.24 of this section. When calculating the by-product emission factor for an FC input gas i for which $\sum_s ES_{i,s}$ equals or exceeds $ES_{imax,f}$, inventory compilers should exclude the consumption of that input gas from the term $\sum$ $Activity_{i,f}$.

EQUATION 6.24 (NEW)
FC BY-PRODUCT SPECIFIC EMISSION FACTOR

$$EF_{k,f} = \frac{\sum_s ES_{k,s}}{\sum_i Activity_{i,f} \bullet (UT_f + \frac{1 - UT_f}{1 - (a_{k,i,f} \bullet d_k)})}$$

Where:

$EF_{k,f}$ = emission factor for FC by-product gas k emitted from facility f, representing 100 percent emissions control system uptime, kg emitted per kg of all FC input gases i consumed

$ES_{k,s}$ = emissions of FC by-product gas k, emitted from stack system s during the sampling period, kg

$Activity_{i,f}$ = consumption of FC input gas i for facility f during the sampling period, kg

UT_f = total uptime of all emissions control systems for facility f during the sampling period, as calculated in Equation 6.27, site-specific fraction. If the stack system does not have emissions control systems on the tools vented to the stack system, the value of this parameter is zero

$a_{k,i,f}$ = estimate of the fraction of by-product k formed from input gas i that is exhausted from process tools equipped with suitable emissions control technologies for facility f, site-specific fraction as determined in Equation 6.11

d_k = Destruction Removal Efficiency (DRE) for FC by-product k, fraction

i = FC input gas

k = FC by-product gas

s = stack system

f = facility

After calculating $EF_{i,f}$, inventory compilers should calculate annual facility-level emissions of each input gas i consumed during the year using Equation 6.25.

EQUATION 6.25 (NEW)
ANNUAL EMISSION OF INPUT GAS I

$$EA_{i,f} = EF_{i,f} \bullet C_{i,f} \bullet UT_f + \frac{EF_{i,f}}{1 - a_{i,f} \bullet d_i} \bullet C_{i,f} \bullet (1 - UT_f)$$

Where:

$EA_{i,f}$ = annual emissions of input gas i from the stack systems that are tested for facility f, kg/year

$EF_{i,f}$ = emission factor for input gas i and facility f representing 100 percent emissions control system uptime, as calculated in Equation 6.23b or 6.23c as appropriate, kg emitted per kg of input gas consumed

$C_{i,f}$ = total consumption of input gas i for facility f for the reporting year, kg/year

UT_f = the total uptime of all emissions control systems for facility f, during the reporting year, as calculated using Equation 6.27 of this section, site-specific fraction

$a_{i,f}$ = estimate of the fraction of gas i emitted from process tools equipped with suitable emissions control technologies, site-specific fraction, as determined in Equation 6.10 for facility f

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

i = input gas

f = facility

After calculating $EA_{i,f}$, inventory compilers should calculate annual facility-level emissions of each FC by-product k formed using Equation 6.26 of this section.

EQUATION 6.26 (NEW)
ANNUAL EMISSION OF FC BY-PRODUCT K

$$EA_{k,f} = EF_{k,f} \bullet \sum_i C_{i,f} \bullet UT_f + EF_{k,f} \bullet \sum_i \frac{C_{i,f} \bullet (1 - UT_f)}{1 - a_{k,i,f} \bullet d_k}$$

Where:

$EA_{k,f}$ = annual emissions of FC by-product k from the stack systems that are tested for facility f, kg/year

$EF_{k,f}$ = emission factor for FC by-product gas k, emitted from facility f representing 100 percent emissions control system uptime, as calculated in Equation 6.24 of this section, kg emitted/kg of all FC input gases consumed

$C_{i,f}$ = total consumption of FC input gas i for facility f for the reporting year, kg

UT_f = the total uptime of all emissions control systems for facility f, during the reporting year as calculated using Equation 6.27 of this section, fraction

$a_{k,i,f}$ = estimate of the fraction of FC by-product gas k formed from input gas i that is exhausted from process tools equipped with suitable emissions control technologies, site-specific fraction as determined in Equation 6.11 for facility f

d_k = Destruction Removal Efficiency (DRE) for FC by-product gas k, fraction

i = FC input gas

k = FC by-product gas

f = facility

Finally, inventory compilers should calculate, for each reporting site, the average uptime of all emissions control equipment connected to process tools for facility f (UT_f), using Equation 6.27. To this end, inventory compilers should account for the total time ($Td_{n,f}$) that any emissions control equipment n connected to process tool(s) in reporting facility f is not in operational mode when at least one of the manufacturing tools connected to emissions control equipment n is in operation, and the total time ($TT_{n,f}$) in which emissions control equipment n has at least one associated manufacturing tool in operation. For determining the amount of tool operating time, inventory compilers may assume that tools that were installed for the whole of the year were operated for 525,600 minutes per year. Inventory compilers should adjust the total minutes to reflect sampling time for the purposes of Equation 6.23 and Equation 6.24. For tools that were installed or uninstalled during the year, inventory compilers should prorate the operating time to account for the days in which the tool was not installed and treat any partial day that a tool was installed as a full day (1,440 minutes) of tool operation. For an emissions control equipment 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. For tools that are idle with no gas flowed through the tool for part of the year, inventory compilers may calculate total tool time using the actual time that gas is flowing through the tool. Inventory compilers should also note that UT_f may be set to one (1) if suitable backup emissions control equipment or interlocking with the process tool is implemented for each emissions control system. Thus, using interlocked process tools or backup emissions control systems reduces uncertainty by eliminating the need to estimate UT for the reporting facility. Facility records such as maintenance records for emissions control systems can also be used to estimate emissions control system uptime.

EQUATION 6.27 (NEW)
AVERAGE EMISSIONS CONTROL SYSTEM UPTIME

$$UT_f = 1 - \frac{\sum_n Td_{n,f}}{\sum_n TT_{n,f}}$$

Where:

UT_f = the average uptime factor for all emissions control systems in fab f, fraction. When this term is used for Equation 6.23 and 6.24, evaluate $Td_{n,f}$, $TT_{n,f}$, and $UT_{n,f}$ for the sampling period

$Td_{n,f}$ = the total time, in minutes, that emissions control system n, connected to process tool(s) in fab f, is not in operational mode

$TT_{n,f}$ = total time, in minutes per year or in minutes of sampling time when used with Equations 6.23 and 6.24, in which the tool(s) connected at any point during the year to emissions control system n, in fab f could be in operation

n = emissions control system

f = facility

6.2.1.2 FLUORINATED LIQUIDS

Fluorinated liquids are used as HTFs for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of electronics manufacturing production processes. Leakage and evaporation of these fluids during use is a source of fluorinated greenhouse gas emissions.

Fluorinated liquid emissions consist primarily of hydrofluoroethers, perfluoropolyethers (including PFPMIE) and other fully fluorinated liquids (perfluorinated amines 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 fluorinated liquids have been marketed in recent years for some applications, but that such materials may be regulated in some regions (e.g. as volatile organic compounds), and this should be considered when choosing alternative fluorinated liquids. Table 6.5 lists fluorinated liquids that are commonly used in the electronics industry, along with their 100-year GWPs. Note that the list of fluorinated liquids in Table 6.5 is not exhaustive and that additional fluorinated liquids may be used.

TABLE 6.5 (NEW)
FLUORINATED LIQUIDS COMMONLY USED IN THE ELECTRONICS INDUSTRY

Chemical Type	Fluorinated Liquid	AR4 or AR5 100-year GWP[1]
PFPMIE Distillates	PFPMIE fractions, boiling points 55-270 °C (Solvay Galden™ HT series, HT-55 through HT-270)	10,300[2]
	PFPMIE fractions, boiling points 200-230 °C (Solvay Galden™ LS series, LS-200 through LS-230)	10,300[2]
	PFPMIE fractions, boiling points 240-260 °C (Solvay Galden™ HS series, HS-240 through HS-260)	10,300[2]
	PFPMIE fractions, boiling points 81-230 °C (Solvay Galden™ DET, D02, D02-TS, D03, and D05)	10,300[2]
	PFPMIE fractions, boiling points 55-135 °C (Solvay Galden™ SV series, SV-55 through SV-135)	10,300[2]
	PFPMIE fractions (Solvay Galden™ Perfluorosolv series)	10,300[2]
Other Fully Fluorinated Liquids	Perfluorotripropylamine (PTPA, 3M™ Fluorinert™ FC-3283/FC-8270)	Not available[3]
	Perfluorotributylamine (PTBA, 3M™ Fluorinert™ FC40/FC-43)	Not available[3]
	Perfluoroisopropylmorpholine (3M™ Fluorinert™ FC-770)	Not available[3]
	Perfluoromethylmorpholine (3M™ Fluorinert™ FC-3284)	Not available[3]
PFCs[4]	C_6F_{14} (Perfluorohexane, 3M™ Fluorinert™ FC-72)	9,300
	C_7F_{16} (Perfluoroheptane, 3M™ Fluorinert™ FC-84)	7,820
	C_8F_{18} (Perfluorooctane, 3M™ Fluorinert™ FC-3255, FC-104)	7,620
	Blend of C_8F_{18} and perfluoro-2-butyltetrahydrofuran (3M™ Fluorinert™ FC-77)	Not available[3]
Saturated HFCs[4]	HFC-4-3-10mee (Chemours Vertrel™ XF)	1,640
	Blends including HFC-43-10mee and/or other saturated HFCs (Chemours Vertrel™ MCA, SDG, SMT, and SFR)	Approximately 150 to 1,000
Hydrofluoroethers	Methoxytridecafluoroheptene alone (Chemours Opteon™ SF10) and blended with trans-1,2-dichloroethylene (Chemours Opteon™ SF79)	Not available[5]
	HFE-347mcc3 (3M™ Novec™ 7000 Engineered Fluid)	575
	HFE-449s1 (3M™ Novec™ HFE-7100)	297
	HFE-569sf2, (3M™ Novec™ HFE-7200)	59
	1 1 1 2 2 3 4 5 5 5-decafluoro-3-methoxy-4-trifluoromethyl-pentane (3M™ Novec™ HFE-7300)	Not available[6]
	3-ethoxy-1,1,1,2,3,4,4,5,5,6,6,6-dodecafluoro-2-trifluoromethyl-hexane (3M™ Novec™ HFE-7500)	Not available[6]
	Blends including HFE-449s1 and HFE-569sf2 (3M™ Novec™ 71DA, 71DE, 71IPA, 72DA, 72DE, 72FL Engineered Fluids)	41-284
Fluorinated Ketones	perfluoro(2-methyl-3-pentanone) (3M™ Novec™ 649 Engineered Fluid/3M™ Novec™ 1230 Fire Protection Fluid, FK 5-1-12	0.1

TABLE 6.5 (NEW) (CONTINUED)
FLUORINATED LIQUIDS COMMONLY USED IN THE ELECTRONICS INDUSTRY

[1] The GWP in the Fourth Assessment Report (AR4) is provided if the compound has a GWP in AR4. Otherwise, the GWP in the Fifth Assessment Report (AR5) is provided.

[2] This is the GWP for the PFPMIE distillate fraction that is sold under the name Solvay Galden HT-70 (Young et al). Solvay has stated that the HT, LS, HS, SV, and Perfluorosolv series, as well as DET, D02, D02-TS, D03, and D05, have similar chemical structures (varying only in their chain lengths) and are manufactured with the same production process. They differ in their molecular weights because they are different fractions of the source "bulk fluid."

[3] The GWPs for these compounds have not been published in the peer-reviewed literature. However, evaluations by the manufacturer indicate that their GWPs are near 10,000 (US Federal Register Volume 78, Issue 66 (April 5, 2013), pp. 20632-37). This is expected given that these compounds are both fully fluorinated and saturated, as are, for example, the PFCs listed above. The US EPA assigns a default 100-year GWP of 10,000 to compounds that are both saturated and fully fluorinated and that do not have chemical-specific GWPs in either the Fourth or the Fifth Assessment Reports.

[4] In addition to the PFCs and HFCs listed here, some facilities reporting emissions under the US EPA Greenhouse Gas Reporting Program have reported emissions of SF_6 and low-boiling point PFCs and HFCs that are used as heat transfer fluids.

[5] The US EPA estimates a 100-year GWP for methoxytridecafluoroheptene of 2.5 (US Federal Register Volume 80, page 42058, July 16, 2015) and a 100-year GWP for trans-1,2-dichloroethylene of less than five due to its structure and brief atmospheric lifetime (US Federal Register Volume 81, page 32241, May 23, 2016).

[6] The GWPs for these compounds have not been published in the peer-reviewed literature. However, based on their similarity to HFEs for which GWPs have been published (saturated HFEs and HCFEs with 3 or more carbon-hydrogen bonds), the US EPA assigns a default 100-year GWP of 270 to these compounds.

There are two methods for estimating emissions from the use of fluorinated liquids. The choice of methods will depend on the availability of inventory data on the use of fluorinated liquids and is outlined in the decision tree (see Figure 6.3, Decision Tree for Estimation of FC Emissions from Fluorinated Liquids, and see Section 1.5 of Chapter 1, Choosing between the Mass Balance and Emission Factor Approach).

TIER 1 – FLUORINATED LIQUIDS

Tier 1 is appropriate when company-specific data are not available on the consumption of fluorinated liquids. Tier 1 factors are available for semiconductor manufacturing (including both factors for heat transfer fluid applications and for testing, packaging and soldering) and for display (for heat transfer fluid applications). It is the less accurate of the two methods for estimating emissions from losses of fluorinated liquids. The method, unlike the Tier 2 method, gives estimates of emissions for three fluorinated liquids that represent the three main types of compounds used as heat transfer fluids globally (see Table 6.18). For any class of electronic products (semiconductor, MEMS, display), the default emission factors are multiplied by the annual production, P. For fluorinated heat transfer fluid applications, P is the area of substrate processed in units of square meters (m^2). For testing, packaging and soldering, P is the number of packaged devices in thousands (kpcs). The result is a set of annual emissions estimates expressed in kg of materials emitted during the manufacture of a particular class of electronic products. The Tier 1 method for estimating emissions from fluorinated liquids is analogous to the Tier 1 method for estimating greenhouse gas emissions during electronic devices manufacturing. The formula is shown in Equation 6.28.

EQUATION 6.28 (UPDATED)
TIER 1 METHOD FOR ESTIMATION OF TOTAL FC EMISSIONS FROM FLUORINATED LIQUIDS

$$FC_i = EF_i \bullet P$$

Where:

FC_i = emissions of fluorinated liquid i, kg

EF_i = emission factor for fluorinated liquid aggregate emissions either per m^2 of substrate consumed during the period (kg/m^2, for heat transfer fluid applications), or per thousand packaged devices, kg/kpcs, for testing, packaging and soldering

P = annual production either in m^2 of substrate used during the production of electronic devices, including test substrates (for heat transfer fluid applications), or in thousands of packaged devices (for testing, packaging and soldering). If annual production in m^2 is not available from an electronics producer, P in m^2 may be calculated as the product of the annual manufacturing capacity and annual plant production capacity utilisation (fraction) of that producer.

For semiconductor manufacturing, it is *good practice* to apply equation 6.28 twice—once to estimate emissions of fluorinated liquids from heat transfer fluid applications and again to estimate emissions of fluorinated liquids from testing, packaging, and soldering—and then to sum the results of both calculations to obtain total emissions of fluorinated liquids. Tier 1 factors for fluorinated liquids are not available for PV. Tier 1 factors are also not available for substrate cleaning. Thus, the Tier 2 approach should be used to estimate fluorinated liquid emissions from these sources.

TIER 2 METHOD – FLUORINATED LIQUIDS

There is one Tier 2 method for estimating actual emissions from the use of any and each fluorinated liquid, applicable to all electronics manufacturing sub-sectors (semiconductor, display MEMS, PV) and to each application (temperature control, device testing, cleaning substrate surfaces and other parts, and soldering). This method is a mass-balance approach that accounts for fluorinated liquid usage over an annual period. This Tier 2 method is appropriate when company-specific data are available; it is the only method applicable to the use of fluorinated liquids for cleaning substrates surfaces and other parts, and for the PV sub-sector. Over the course of a year, fluorinated liquids are used to fill newly purchased equipment and to replace fluorinated liquid loss from equipment operation through evaporation. Inventory compilers should provide the chemical composition of the fluid(s) for which emissions are estimated for each application. The method is expressed in Equation 6.29.

EQUATION 6.29 (UPDATED)
TIER 2 METHOD FOR ESTIMATION OF FC EMISSIONS FROM FLUORINATED LIQUIDS

$$FC_i = \rho_i \bullet (I_{i,t-1} + P_{i,t} - N_{i,t} + R_{i,t} - I_{i,t} - D_{i,t})$$

Where:

FC_i = emissions of fluorinated liquid i, kg

ρ_i = density of fluorinated liquid i, kg/litre

i = fluorinated liquid

$I_{i,t-1}$ = inventory of liquid FC_i in containers other than equipment at the beginning of the reporting year, litres 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

$P_{i,t}$ = acquisitions of liquid FC_i during the reporting year, 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, litres

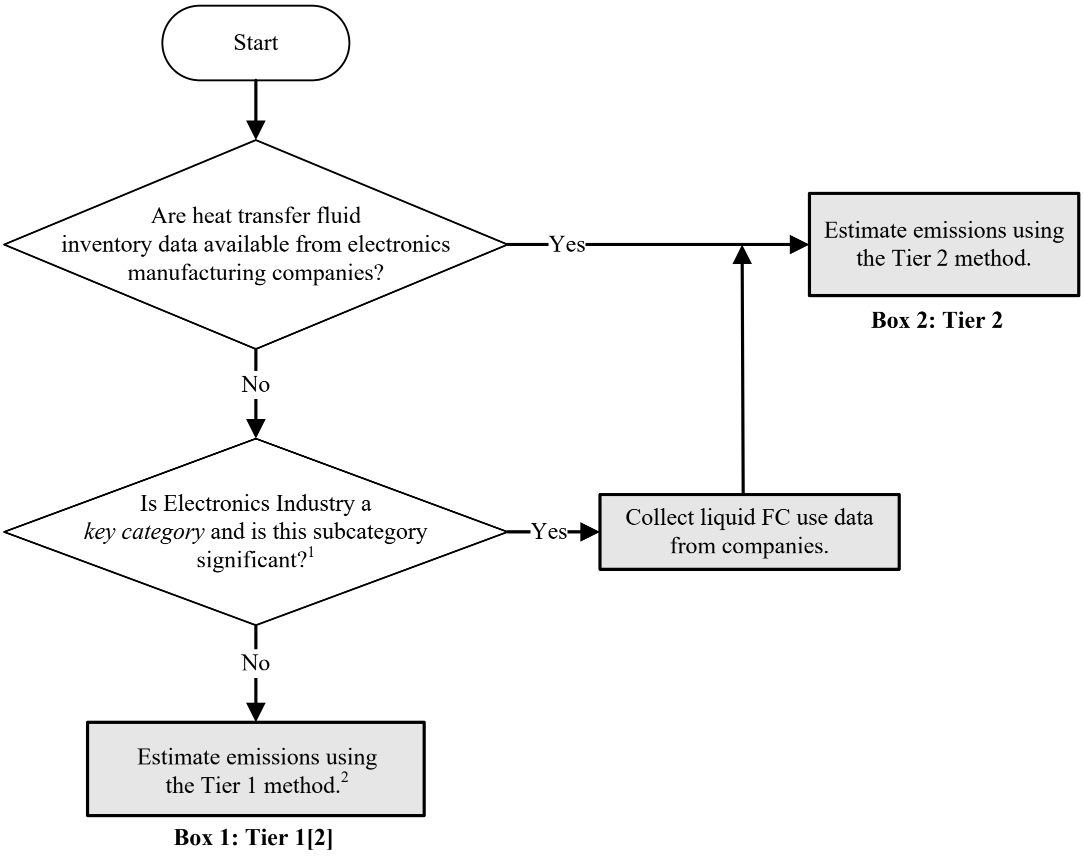
$N_{i,t}$ = total nameplate capacity (full and proper charge) of equipment that uses fluorinated liquid i and that is newly installed in the reporting facility during the reporting year, litres

$R_{i,t}$ = total nameplate capacity (full and proper charge) of equipment that uses fluorinated liquid i and that is removed from service in the reporting facility during the reporting year, litres

$I_{i,t}$ = inventory of liquid FC_i in containers other than equipment at the end of the reporting year, litres in stock or storage

$D_{i,t}$ = disbursements of fluorinated liquid i, including amounts returned to chemical suppliers, sold with or inside of equipment, and sent off-site for verifiable recycling or destruction, litres. Disbursements should include only amounts that are properly stored and transported so as to prevent emissions in transit

Figure 6.3 (Updated) Decision tree for estimation of emissions from fluorinated liquids 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.
2. Substrate cleaning (any sub-sector) and any application in the PV sub-sector require use of Tier 2 method.

6.2.2 Choice of emission factors

This section provides the default emission factors that should be used for reporting emissions under the Tier 1 and Tier 2 methods. Please refer to the corresponding emission factor tables (Tables 6.6 to 6.13 and Tables 6.17 and 6.18) for each method.

The main sources of default emission factors are the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I), the *2006 IPCC Guidelines* (Volume 3, Chapter 6), the World Semiconductor Council (2011, 2012, 2014 and 2016), the World Display device Industry Cooperation Committee, and industry surveys conducted during the *2019 Refinement*.

In the case where a new input gas is used for which no default emission factor $(1\text{-}U_i)$ has been established, facilities can estimate emissions using the Tier 2 methods and assume a default emission factor of $(1\text{-}U_i) = 0.8$ with by-product emission factors of $B_{CF4,i}=0.15$ and $B_{C2F6,i}=0.05$. However, this provision could lead to incomplete and inaccurate results if the use of the new chemical leads to the formation of by-products other than CF_4 and C_2F_6 or if the default emission factors fail to accurately represent actual emissions from the new gas or process. Thus, reporters should measure the emission factors for the new gas or process and use a partial Tier 3a method to account for emissions resulting from the use of the new chemical or new process if the consumption of the new gas exceeds 1 percent of the facility's GHG consumption by mass.

6.2.2.1 GASEOUS FLUORINATED COMPOUNDS AND NITROUS OXIDE

TIER 1

The default emission factors for the Tier 1 method are presented in Table 6.6 below. Because the Tier 1 default emission factors for the semiconductor sector in Table 6.6 are based on a 50/50 split between 200mm and 300mm production, it is *good practice to use* the Tier 1 default emission factors for the semiconductor sector that are available in the *2006 IPCC Guidelines* in cases where the wafer size produced is known to be 200 mm or smaller.

In using Tier 1, it is not *good practice* to modify, in any way, the set of greenhouse gases or the values of the emission factors assumed in Table 6.6. 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_4 to estimate the emissions of CF_4 from semiconductors and combine it with the results of other gases from a Tier 2 or Tier 3 method. It should also be noted that the Tier 1 emission factors presented in Table 6.6 should not be used for any purpose other than estimating annual process gas-aggregate emissions from semiconductor, display, MEMS, or PV manufacturing for compilation of the national greenhouse gas inventory. Tier 1 emissions for the semiconductor sub-sector are calculated based on the surface area of wafer produced. Display emissions are calculated based on the surface area of input glass corresponding to array processes, i.e. the processes used to manufacture the thin film transistors that are part of the display devices. Note that the array input glass area is different than the input glass area used for the manufacturing of colour filters used in display devices, which does not involve the use (or emissions) of fluorinated GHGs. Also note that the Tier 1 factors for MEMS are highly uncertain due to the fact that they were generated from a limited data set. Additionally, as previously discussed in the Choice of Method section, the high Tier 1 emission factor for SF_6 corresponds to a MEMS-specific process consisting of etching vias through the substrate, a process which consumes significant amounts of SF_6.

TABLE 6.6 (UPDATED)
TIER 1 GAS-SPECIFIC EMISSION FACTORS FOR PROCESS GHG EMISSIONS FROM ELECTRONICS MANUFACTURING

Electronics industry subsector	CF_4	C_2F_6	C_3F_8	C_4F_6	$c\text{-}C_4F_8$	C_4F_8O	C_5F_8	CHF_3	CH_2F_2	NF_3	SF_6	N_2O
Semiconductors, kg/m^2	0.36	0.12	0.03	0.003	0.01	7E-5	0.001	0.05	0.003	0.15	0.05	1.01
Display, g/ array input glass area m^2	0.65				0.001			0.0024		1.29	4.14	17.06
PV, g/m^2	5	0.2										
MEMS, kg/m^2	0.015				0.076						1.86	

Sources:

The Tier 1 emission factors for the display sub-sector were provided by the World Display device Industry Cooperation Committee.

The Tier 1 emission factors for the semiconductor sub-sector were provided by the World Semiconductor Council. The factors are based on seven years of data collected by the regions comprising the World Semiconductor Council (WSC), i.e. China, Chinese Taipei, Europe, Japan, Korea, and the United States. Included is data for facilities operated by WSC companies outside the WSC regions e.g., Singapore. The factors are calculated starting from the purchased quantities of the listed gases and by considering the emission factors reported in the Table 6.7 for Tier 2a, including the formation of by-products. The emissions calculated in this way have then been divided by the total area of silicon produced. As the Tier 2a default emission factors used to develop the Tier 1 default emission factors for the semiconductor sector in Table 6.7 assumed a 50/50 split between 200mm and 300mm production, it is *good practice to use* the Tier 1 default emission factors for the semiconductors sector that are available in the *2006 IPCC Guidelines* in cases where the wafer size produced is known to be 200 mm or smaller.

TIER 2

The default emission factors for the Tier 2 methods are presented in Tables 6.7 to 6.13 and Table 6.17 below.

Note that F_2 and COF_2 are included in the list of input gases for the Tier 2 methods because these gases are known to be used for TFD chamber cleaning and because the use of F_2 and COF_2 for chamber cleaning can lead to the formation of CF_4 and other high-GWP by-products, but no data was available to derive emission factors for these gases. Note also that, although COF_2 is a known by-product of chamber cleaning processes using fluorinated carbon gases (e.g. CF_4, C_2F_6, etc.), no by-product factor for COF_2 (i.e. $B_{COF2,i}$) was included in the Tier 2 default tables dues to the low GWP (~1) and short atmospheric life of COF_2.

TABLE 6.7 (UPDATED)
TIER 2A METHOD – DEFAULT EMISSION FACTORS (FRACTIONS) FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING AND FROM MEMS MANUFACTURING UNDER CERTAIN CONDITIONS**

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_3F_8 Remote**	**C_4F_6**	**c-C_4F_8**	**C_4F_8O**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**C_2HF_5**	**NF_3 Remote**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O other**	**COF_2**	**F_2**
$(1-U_i)$	0.73	0.55	0.4	0.063	0.15	0.13	0.14	0.086	0.46	0.2	0.34	0.064	0.02	0.18	0.55	0.78	1.0	NM	NM
B_{CF4}	NA	0.19	0.2	NA	0.06	0.099	0.13	0.053	0.081	0.061	0.029	0.077	0.034	0.067	0.12	NA	NA	NM	NM
B_{C2F6}	0.042	NA	0.000018	NA	0.062	0.02	0.045	0.047	0.046	0.044	0.01	0.024	NA	0.015	0.095	NA	NA	NM	NM
B_{C3F8}	NA	NA	NA	NA	NA	NA	NA	0.000055	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F6}	0.00066	NA	NA	NA	NA	0.0017	NA	NA	0.000041	NA	0.0011	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F8}	0.0015	NA	NA	NA	0.0051	NA	NA	NA	0.00028	0.071	0.0067	NA	NA	NA	NA	NA	NA	NA	NA
B_{C5F8}	0.00042	NA	NA	NA	NA	0.0035	NA	NA	0.00068	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{CH3F}	0.0024	NA	0*	NA	0.00064	0.0004	NA	NA	0.016	0.0043	NA	NA	NA	0.0022	0.0009	NA	NA	NA	NA
B_{CH2F2}	0.0063	NA	NA	NA	0.00003	0.00026	NA	NA	0.0011	NA	0.0021	NA	NA	0.00023	0.0000021	NA	NA	NA	NA
B_{CHF3}	0.039	0.002	0.0000012	NA	0.018	0.022	NA	0.0053	NA	0.057	0.015	NA	NA	0.0068	0.0014	NA	NA	NA	NA

Source: Data collected under the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I); subsets of the data are available at https://www.regulations.gov/docket?D=EPA-HQ-OAR-2011-0028.

*$<10^{-7}$

** Tier 2a default factors for semiconductor manufacturing may be applied to MEMS manufacturing processes that are carried out using semiconductor manufacturing tools when such MEMS processes are similar to semiconductor manufacturing processes (for further details see discussion in the Choice of method section, in particular footnote 3).

NA = Not Applicable; NM = Not Measured (but known to occur). If a new gas and process combination are used that accounts for less than 1 percent of facility fluorinated GHG consumption by mass and (1-U) is NM or not listed, compiler may assume (1-U) = 0.8, B_{CF4} = 0.15, B_{C2F6} = 0.05.

TABLE 6.8 (NEW)
TIER 2A, 2B AND 3B METHODS – DEFAULT WEIGHTING FACTORS $\gamma_{I,P}$ AND $\gamma_{K,I,P}$ FOR SEMICONDUCTOR AND MEMS MANUFACTURING UNDER CERTAIN CONDITIONS*

Tier, input gas ($\gamma_{i,p}$) vs. byproduct ($\gamma_{k,i,p}$), and wafer size	**CF_4 (IPC or ITC)/ EWC**	**C_2F_6 IPC/ EWC**	**c-C_4F_8 IPC/ EWC**	**NF_3 (IPC or ITC) / EWC**	**SF_6 IPC/ EWC**	**NF_3 RPC/ EWC**	**CF_4 RPC/ EWC**	**C_3F_8 RPC/ EWC**	**N_2O TFD/ other**
Tier 2a									
$\gamma_{i,p}$	13†	9.3	4.7	14†	11				
$\gamma_{CF4,i,p}$	NA	23	6.6	63	8.5				
$\gamma_{C2F6,i,p}$	NA	NA	NA	NA	3.4				
Tier 2b									
$\gamma_{i,p}$ (≤200 mm wafer size)	13†	9.3	4.7	2.9†	11				
$\gamma_{CF4,i,p}$ (≤200 mm wafer size)	NA	23	6.6	110	8.5				
$\gamma_{C2F6,i,p}$ (≤200 mm wafer size)	NA	NA	NA	NA	3.4				
$\gamma_{i,p}$ (300 mm wafer size)	NM	NM	NM	26†	NM				
$\gamma_{CF4,i,p}$ (300 mm wafer size)	NA	NA	NA	17	NA				
Tier 3b									
$\gamma_{i,p}$ (both ≤200 mm and 300 mm wafer size)	13†	9.3	4.7	14†	11	5.7	NM	NM	25
$\gamma_{CF4,i,p}$ (both ≤200 mm and 300 mm wafer size)	NA	23	6.6	63	8.5	57	NA	NA	NA
$\gamma_{C2F6,i,p}$ (both ≤200 mm and 300 mm wafer size)	NA	NA	NA	NA	3.4	NA	NA	NA	NA
$\gamma_{i,p}$ (≤200 mm wafer size)	13†	9.3	4.7	2.9†	11	1.4	NM	NM	48
$\gamma_{CF4,i,p}$ (≤200 mm wafer size)	NA	23	6.6	110	8.5	35	NM	NA	NA
$\gamma_{C2F6,i,p}$ (≤200 mm wafer size)	NA	NA	NA	NA	3.4	NA	NA	NA	NA
$\gamma_{i,p}$ (300 mm wafer size)	NM	NM	NM	26†	NM	10	NM	NM	2.4
$\gamma_{CF4,i,p}$ (300 mm wafer size)	NA	NA	NA	17	NA	78	NA	NA	NA

Source: Survey of industrial facility data conducted by the authors of Chapter 6.

*Gamma weighting factors for semiconductor manufacturing may be applied to MEMS manufacturing processes that are carried out using tools and processes similar to those used to manufacture semiconductors (for further details see discussion in the Choice of method section, in particular footnote 3).

† The gamma values for (IPC or ITC)/EWC for 200 mm were developed based on IPC only and the values for 300 mm were developed based on the total emissions and tool count from ITC and IPC. Gamma is assigned based on analogy due to similar emission factors for IPC and ITC, where known, for the same gas and wafer size. For all other cases where no gamma has been measured and a gamma is needed, compiler may assume $\gamma_i = 10$, $\gamma_k = 10$.

TABLE 6.9 (NEW)
TIER 2B METHOD – DEFAULT EMISSION FACTORS (FRACTIONS) FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING AND FROM MEMS MANUFACTURING UNDER CERTAIN CONDITIONS*

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_3F_8 Remote**	**C_4F_6**	**c-C_4F_8**	**C_4F_8O**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**C_2HF_5**	**NF_3 Remote**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O other**	**COF_2**	**F_2**
≤200 mm wafer size																			
(1-U_i)	0.79	0.55	0.4	NA	0.083	0.12	0.14	0.072	0.51	0.13	0.7	0.064	0.028	0.18	0.58	1.0	1.0	NM	NM
B_{CF4}	NA	0.19	0.2	NA	0.095	0.11	0.13	NA	0.085	0.079	NA	0.077	0.015	0.11	0.13	NA	NA	NM	NM
B_{C2F6}	0.027	NA	NA	NA	0.073	0.019	0.045	0.014	0.035	0.025	0.0034	0.024	NA	0.0059	0.10	NA	NA	NM	NM
B_{C3F8}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C5F8}	0.00077	NA	NA	NA	NA	0.0043	NA	NA	0.0012	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{CHF3}	0.06	0.002	NA	NA	0.066	0.02	NA	0.0039	NA	0.049	NA	NA	NA	NA	0.0011	NA	NA	NA	NA
300 mm wafer size																			
(1-U_i)	0.65	0.8	0.3	0.063	0.15	0.18	NA	0.1	0.38	0.2	0.32	NA	0.018	0.18	0.29	0.5	1.0	NM	NM
B_{CF4}	NA	0.21	0.21	NA	0.059	0.045	NA	0.11	0.076	0.06	0.031	NA	0.038	0.04	0.034	NA	NA	NM	NM
B_{C2F6}	0.061	NA	0.18	NA	0.062	0.027	NA	0.083	0.062	0.044	0.011	NA	NA	0.02	0.041	NA	NA	NM	NM
B_{C3F8}	NA	NA	NA	NA	NA	NA	NA	0.00012	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
--B_{C4F6}	0.0015	NA	NA	NA	NA	0.0090	NA	NA	0.0001	NA	0.0012	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F8}	0.0033	NA	NA	NA	0.0051	NA	NA	NA	0.00067	0.072	0.007	NA	NA	NA	NA	NA	NA	NA	NA
B_{CH3F}	0.0053	NA	0.00073	NA	0.00065	0.0022	NA	NA	0.037	0.0044	NA	NA	NA	0.0036	0.0082	NA	NA	NA	NA
B_{CH2F2}	0.014	NA	NA	NA	0.00003	0.0014	NA	NA	0.0026	NA	0.0023	NA	NA	0.00039	0.00002	NA	NA	NA	NA
B_{CHF3}	0.013	NA	0.012	NA	0.017	0.029	NA	0.0069	NA	0.057	0.016	NA	NA	0.011	0.0039	NA	NA	NA	NA

Source: Data collected under the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I); subsets of the data are available at https://www.regulations.gov/docket?D=EPA-HQ-OAR-2011-0028.

* Tier 2b default factors for semiconductor manufacturing may be applied to MEMS manufacturing processes that are carried out using semiconductor manufacturing tools when such MEMS processes are similar to semiconductor manufacturing processes (for further details see discussion in the Choice of method section, in particular footnote 3).

NA = Not Applicable; NM = Not Measured (but known to occur). If a new gas and process combination are used that accounts for less than 1 percent of facility fluorinated GHG consumption by mass and (1-U) is NM, compiler may assume (1-U) = 0.8, B_{CF4} = 0.15, B_{C2F6} = 0.05.

TABLE 6.10 (NEW)
TIER 2C METHOD (≤200 MM) – DEFAULT EMISSION FACTORS (FRACTIONS) FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING AND FROM MEMS MANUFACTURING UNDER CERTAIN CONDITIONS*

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_4F_6**	**c-C_4F_8**	**C_4F_8O**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**C_2HF_5**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O other**	**COF_2**	**F_2**
Etching or Wafer Cleaning (EWC)																	
$(1-U_i)$	0.73	0.72	NA	0.083	0.14	NM	0.072	0.51	0.13	0.7	0.064	0.19	0.55	NA	NA	NM	NM
B_{CF4}	NA	0.1	NA	0.095	0.11	NM	NA	0.085	0.079	NA	0.077	0.004	0.13	NA	NA	NM	NM
B_{C2F6}	0.041	NA	NA	0.073	0.037	NM	0.014	0.035	0.025	0.0034	0.024	0.025	0.11	NA	NA	NM	NM
B_{C5F8}	0.0012	NA	NA	NA	0.0086	NA	NA	0.0012	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{CHF3}	0.091	0.047	NA	0.066	0.04	NA	0.0039	NA	0.049	NA	NA	NA	0.0012	NA	NA	NA	NA
Remote Plasma Cleaning (RPC)																	
$(1-U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.028	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.015	NA	NA	NA	NA	NA
In-situ Plasma Cleaning (IPC)																	
$(1-U_i)$	0.92	0.55	0.4	NA	0.1	0.14	NA	NA	NA	NA	NA	0.18	NM	NA	NA	NM	NA
B_{CF4}	NA	0.19	0.2	NA	0.11	0.13	NA	NA	NA	NA	NA	0.14	NM	NA	NA	NM	NA
B_{C2F6}	NA	NA	NA	NA	NA	0.045	NA	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA
Thin Film Deposition (TFD)																	
$(1-U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0	NA	NA	NA
Other																	
$(1-U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0	NA	NA

Source: Data collected under the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I); subsets of the data are available at https://www.regulations.gov/docket?D=EPA-HQ-OAR-2011-0028.

* Tier 2c default factors for semiconductor manufacturing may be applied to MEMS manufacturing processes that are carried out using semiconductor manufacturing tools when such MEMS processes are similar to semiconductor manufacturing processes (for further details see discussion in the Choice of method section, in particular footnote 3).

NA = Not Applicable; NM = Not Measured (but known to occur). No emission factor data was available for in-situ thermal cleaning for ≤200 mm, but the process is known to be used. If a new gas and process combination are used that accounts for less than 1 percent of facility fluorinated GHG consumption by mass and (1-U) is NM, compiler may assume (1-U) = 0.8, B_{CF4} = 0.15, B_{C2F6} = 0.05.

TABLE 6.11 (NEW)
TIER 2C METHOD (300 MM) – DEFAULT EMISSION FACTORS (FRACTIONS) FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING AND FROM MEMS MANUFACTURING UNDER CERTAIN CONDITIONS*

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_4F_6**	**c-C_4F_8**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O other**	**COF_2**	**F_2**
Etching and Wafer Cleaning (EWC)															
(1-U_i)	0.65	0.8	0.3	0.15	0.18	0.1	0.38	0.2	0.32	0.16	0.29	NA	NA	NM	NM
B_{CF4}	NA	0.21	0.21	0.059	0.045	0.11	0.076	0.06	0.031	0.045	0.034	NA	NA	NM	NM
B_{C2F6}	0.061	NA	0.18	0.062	0.027	0.083	0.062	0.044	0.011	0.045	0.041	NA	NA	NM	NM
B_{C3F8}	NA	NA	NA	NA	NA	0.00012	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F6}	0.0015	NA	NA	NA	0.0094	NA	0.0001	NA	0.0012	NA	NA	NA	NA	NA	NA
B_{C4F8}	0.0033	NA	NA	0.0051	NA	NA	0.00067	0.072	0.007	NA	NA	NA	NA	NA	NA
B_{CH3F}	0.0053	NA	0.00073	0.00065	0.0022	NA	0.037	0.0044	NA	0.008	0.0082	NA	NA	NA	NA
B_{CH2F2}	0.014	NA	NA	0.00003	0.0014	NA	0.0026	NA	0.0023	0.00086	0.00002	NA	NA	NA	NA
B_{CHF3}	0.013	NA	0.012	0.017	0.029	0.0069	NA	0.057	0.016	0.025	0.0039	NA	NA	NA	NA
Remote Plasma Cleaning (RPC)															
(1-U_i)	NA	NA	0.063	NA	NA	NA	NA	NA	NA	0.018	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.038	NA	NA	NA	NA	NA
In-situ Plasma Cleaning (IPC)															
(1-U_i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.2	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.037	NA	NA	NA	NA	NA
In-situ Thermal Cleaning (ITC)															
(1-U_i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.28	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.01	NA	NA	NA	NA	NA

TABLE 6.11 (NEW) (CONTINUED)
TIER 2C METHOD (300 MM) – DEFAULT EMISSION FACTORS (FRACTIONS) FOR GHG EMISSIONS FROM SEMICONDUCTOR MANUFACTURING AND FROM MEMS MANUFACTURING UNDER CERTAIN CONDITIONS*

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_4F_6**	**c-C_4F_8**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O other**	**COF_2**	**F_2**
TFD															
(1-U_i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.5	NA	NA	NA
Other															
(1-U_i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0	NA	1.0

Source: Data collected under the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I); subsets of the data are available at https://www.regulations.gov/docket?D=EPA-HQ-OAR-2011-0028.

* Tier 2c default factors for semiconductor manufacturing may be applied to MEMS manufacturing processes that are carried out using semiconductor manufacturing tools when such MEMS processes are similar to semiconductor manufacturing processes (for further details see discussion in the Choice of method section, in particular footnote 3).

NA = Not Applicable; NM = Not Measured (but known to occur). If a new gas and process combination are used that accounts for less than 1 percent of facility fluorinated GHG consumption by mass and (1-U) is NM, compiler may assume (1-U) = 0.8, B_{CF4} = 0.15, B_{C2F6} = 0.05.

Table 6.12 (Updated)
Tier 2c method – default emission factors (fractions) for GHG emissions from Display manufacturing

Process Gas	CF_4	$c\text{-}C_4F_8$	CHF_3	NF_3	SF_6	N_2O
Etching						
$(1-U_i)$	0.6	0.1	0.2	0.11	0.3	NA
B_{CF4}	NA	0.009	0.07	NA	NA	NA
B_{C2F6}	NA	NA	0.05	NA	NA	NA
B_{CHF3}	NA	0.02	NA	NA	NA	NA
Remote plasma cleaning (RPC)						
$(1-U_i)$	NA	NA	NA	0.03	NA	NA
In-situ plasma cleaning (IPC)						
$(1-U_i)$	NA	NA	NA	0.3	0.9	NA
Thin film deposition (TFD)						
$(1-U_i)$	NA	NA	NA	NA	NA	0.63

Table 6.13 (Updated)
Tier 2c Method -- Default emission factors (fractions) for GHG emissions from PV manufacturing

Process Gas (i)	CF_4	C_2F_6	CHF_3	CH_2F_2	C_3F_8	$c\text{-}C_4F_8$	NF_3 Remote	NF_3	SF_6	C_4F_6	C_5F_8	C_4F_8O	F_2	COF_2
Etch 1-Ui	0.7	0.4	0.4	NA	NA	0.2	NA	NA	0.4	NA	NA	NA	NA	NA
TFD 1-Ui	NA	0.6	NA	NA	0.1	0.1	NA	0.3	0.4	NA	NA	NA	NA	NA
Etch B_{CF4}	NA	0.2	NA	NA	NA	0.1	NA	NA	NA	NA	NA	NA	NA	NA
Etch B_{C2F6}	NA	NA	NA	NA	NA	0.1	NA	NA	NA	NA	NA	NA	NA	NA
TFD B_{CF4}	NA	0.2	NA	NA	0.2	0.1	NA	NA	NA	NA	NA	NA	NA	NA

Notes: NA denotes not applicable based on currently available information

Table 6.14 (New)
Methods and procedures for conducting emissions tests for stack systems

For each stack system for which you use Tier 3b method to calculate annual emissions	You should	Using the method cited below or equivalent
For each fluorinated GHG	Measure the concentration in the stack system.	Using U.S. EPA Method 320 at 40 CFR part 63, appendix A or ASTM D6348-03. Conduct the test run for a minimum of 8 hours for each stack system.
	Select sampling port locations and the number of traverse points.	U.S. EPA Method 1 or 1A at 40 CFR part 60, appendix A-1.
	Determine gas velocity and volumetric flow rate.	U.S. EPA Method 2, 2A, 2C, 2D, 2F or 2G at 40 CFR part 60, appendix A-1 and A-2.
	Determine gas molecular weight.	U.S. EPA Method 3, 3A, or 3B at 40 CFR part 60, appendix A-2 using the same sampling site and time as the fluorinated GHG sampling.
	Measure gas moisture content.	U.S. EPA Method 4 at 40 CFR part 60, appendix A-3 or using FTIR.

TABLE 6.15 (NEW)
MAXIMUM FIELD DETECTION LIMITS (FDL) APPLICABLE TO FLUORINATED COMPOUNDS (FC) CONCENTRATION MEASUREMENTS FOR STACK SYSTEMS

Fluorinated GHG Analyte	**Maximum Field detection limit (ppbv[*])**
CF_4	20
C_2F_6	20
C_3F_8	20
C_4F_6	20
c–C_4F_8	20
C_5F_8	20
CHF_3	20
CH_2F_2	40
CH_3F	40
NF_3	20
SF_6	4
Other fully fluorinated GHGs	20
Other fluorinated GHGs	40

[*] ppbv = parts per billion by volume

EMISSIONS CONTROL TECHNOLOGY FACTORS

Since 2006, the performance of emissions control devices in production conditions has been more extensively characterized, and the *2019 Refinement* provides revised default DRE values for a larger basket of gases (see Table 6.17). Figure 6.4 provides guidance for deciding when a particular emissions control technology may be suitable to abate fluorinated compounds (FCs) and N_2O emissions from electronic devices manufacturing, when default emissions control technology factors may be used, or when site-specific destruction removal efficiencies can or should be measured. With regards to emissions control equipment, "exhaust gases" 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.

First, in the case of emissions control technologies using hydrocarbon fuel, inventory compilers should consider whether emissions to be abated originate from NF_3- or F_2-based remote plasma clean (RPC) applications (step [1] in Figure 6.4). These processes lead to the formation of significant amounts of molecular fluorine (F_2) originating from the conversion of NF_3 into F_2 or the limited utilization efficiency of F_2 (when the latter is used as a cleaning precursor). When the exhaust gases contain large amounts of F_2 and when hydrocarbon-fuel-based combustion emissions control technology is used, direct reaction with the hydrocarbon fuel and F_2 to form CF_4 can occur.[11,12,13] Unless the emissions control system manufacturer (referred to below as the "original equipment manufacturer" or OEM") or the electronic devices manufacturer can certify that the rate of conversion from F_2 to CF_4 or from NF_3 to CF_4 is <0.1 percent on a mass basis, a default value of $AB_{NF3,CF4} = 0.093$ or $AB_{F2,CF4} = 0.0116$ should be used in Equations 6.7 (Tier 2a/2b) or Equation 6.15 (Tier 2c/3a) to estimate the amount of CF_4 produced within and emitted from the emissions control device (step [2] in Figure 6.4).

Second, inventory compilers should verify whether site-specific emissions control technologies are suitable for the gas to be abated (step [3] in Figure 6.4). In doing so, inventory compilers should consult Table 6.16, where an 'X' indicates which technology is, in principle, capable of abating a certain gas. Definitions of common emissions control technologies are provided in the footnotes of Table 6.16. Note that the absence of an 'X' in Table 6.16 for a particular combination of gas and emissions control technology does not necessarily preclude the ability of the technology to abate a particular gas, but such ability should be supported by experimental data from the original equipment manufacturer (OEM) or the electronic devices manufacturer. Because new emissions control technologies could emerge, a 'T' in last row of Table 6.16 indicates that, to be considered as being suitable for treating a specific gas, the OEM or the electronic devices manufacturer would need to provide testing data to show that, when the new emissions control technology is tested under representative gas flow conditions, defaults (or site-specific) DREs can be achieved using an industry-accepted measurement methodology that accounts for dilution.[14,15,16]

Third, inventory compilers should verify that emissions control systems have been tested and are certified by the OEM(s) to meet the default DRE values indicated in Table 6.17 (step [4] in Figure 6.4). To do so, the reporting facility should define its worst-case scenarios as the highest total FC or N_2O flows through each model of emissions control systems (gas by gas and process type by process type across the facility) and highest total flow scenarios (with N_2 dilution accounted for, see step [6]), and the reporting facility should request the emissions control equipment manufacturer(s) to certify that the default DREs can be met in the worst-case scenarios for each model of emissions control systems. In the case that the OEM(s) cannot certify that the emissions control system(s) can meet the default DRE values of Table 6.17 (step [5] of Figure 6.4), the corresponding DRE value should be set to zero (0 percent), or the reporting facility may set the DRE value using DREs measured by the electronics device manufacturer (site-specific DREs) or certified by the OEM using an industry-accepted measurement methodology for the site-specific worst case scenarios as previously described (OEM certified DREs). If a facility wishes to claim a DRE value higher than the default DRE values of Table 6.17, it should perform site specific testing (step [7] of Figure 6.4). When using site-specific DREs, a suitable DRE testing frequency should be adopted to ensure

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[11] Gray, Fraser, and Afroza Banu, "Influence of CH4-F2 mixing on CF4 by-product formation in the combustive abatement of F2," Research Disclosure

[12] Czerniak, Mike, "Mechanisms for PFC Formation in CVD Applications," presented at SESHA 2018

[13] Li, Shou-Nan, Jung-Nan Hsu, Hui-Ya Shih, Shu-Jen Lin and Jen-Liang Hong (2002). "FTIR spectrometers measure scrubber abatement efficiencies." Solid State Technology, 45: 157-165.

[14] Protocol for Measuring Destruction or removal Efficiency (DRE) of Fluorinated Greenhouse Gas Abatement Equipment in Electronics Manufacturing. United States Environmental Protection Agency. EPA 430-R-10-003 (2010). https://www.epa.gov/sites/production/files/2016-02/documents/dre_protocol.pdf

[15] Guideline for Environmental Characterization of Semiconductor Process Equipment – Revision 2. International SEMATECH Manufacturing Initiative. Technology Transfer #06124825B-ENG (2009). http://www.lexissecuritiesmosaic.com/gateway/FedReg/document_4825beng.pdf

[16] JEITA Guideline for F-GHG Characterization and Management. Japan Electronics and Information Technologies Industries Association (2011). http://semicon.jeita.or.jp/committee/docs/F-GHG_guideline_20110520_en.pdf

that at least 5 percent of the installed emissions control equipment population is tested annually for a representative sample of process applications. To use OEM-specific DREs, it is *good practice* to state the test conditions and range of input process gas and total gas for which the DRE is applicable.

Fourth, to ensure that DRE values remain accurate, it is essential that facilities ensure that emissions control equipment is installed, maintained and operated per manufacturer's specifications. Proper operation requires all parameters to be within manufacturer's specifications, including items such as vacuum pumps' purges, fuel / oxidizer settings, supply and exhaust flows and pressures, and utilities to the emissions control equipment (fuel gas flow and pressure, calorific value, water quality, flow & pressure, extract flow and pressure, etc.). Please note that not exceeding the emissions control equipment suppliers' maximum flow specifications requires that all gases, including post-process-chamber purges, are taken into account. Also note that some vacuum pumps' purge flow indicators are inaccurate and could deliver higher-than-indicated purge flows, exceeding the emissions control equipment suppliers' maximum flow specifications. Accurate flows can be determined using a calibrated portable mass flow meter (MFM) with a minimum accuracy of +/- 5 percent. It is suggested to perform calibration every time a vacuum pump is serviced or exchanged.

TABLE 6.16 (NEW)
EMISSIONS CONTROL EQUIPMENT SUITABILITY TABLE FOR DESTRUCTION REMOVAL EFFICIENCY (DRE) OF PROCESS GHG EMISSIONS

Emissions Control Equipment Technology	Process GHG Emission														
	CF_4	C_2F_4	C_2F_6	C_3F_8	C_4F_6	$c\text{-}C_4F_8$	C_4F_8O	C_5F_8	CHF_3	CH_2F_2	CH_3F	C_2HF_5	NF_3	SF_6	N_2O
Cartridge (Media consumed)						X			X				X	X	X
Catalyst (Media not consumed)	X												X	X	X
Hot-wet (electrical) < 850° C															
Hot-wet (electrical) > 850° C				X	X	X							X		
Plasma	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
New technology	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T

'X' indicates that the technology is potentially suitable to use the default DRE for the particular gas.

"T" indicates that, to be considered as being suitable for treating a specific gas, the OEM would need to provide testing data to show that, when the new emissions control technology is tested on worst-case gas flow conditions, defaults (or site-specific) DREs can be achieved using an industry-accepted measurement methodology that accounts for dilution.

Emissions Control Equipment technology definitions:

Cartridge – Any form of dry-bed passive gas treatment, either heated or working at ambient-temperature. The active media is consumed by reaction with the target gas.

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.

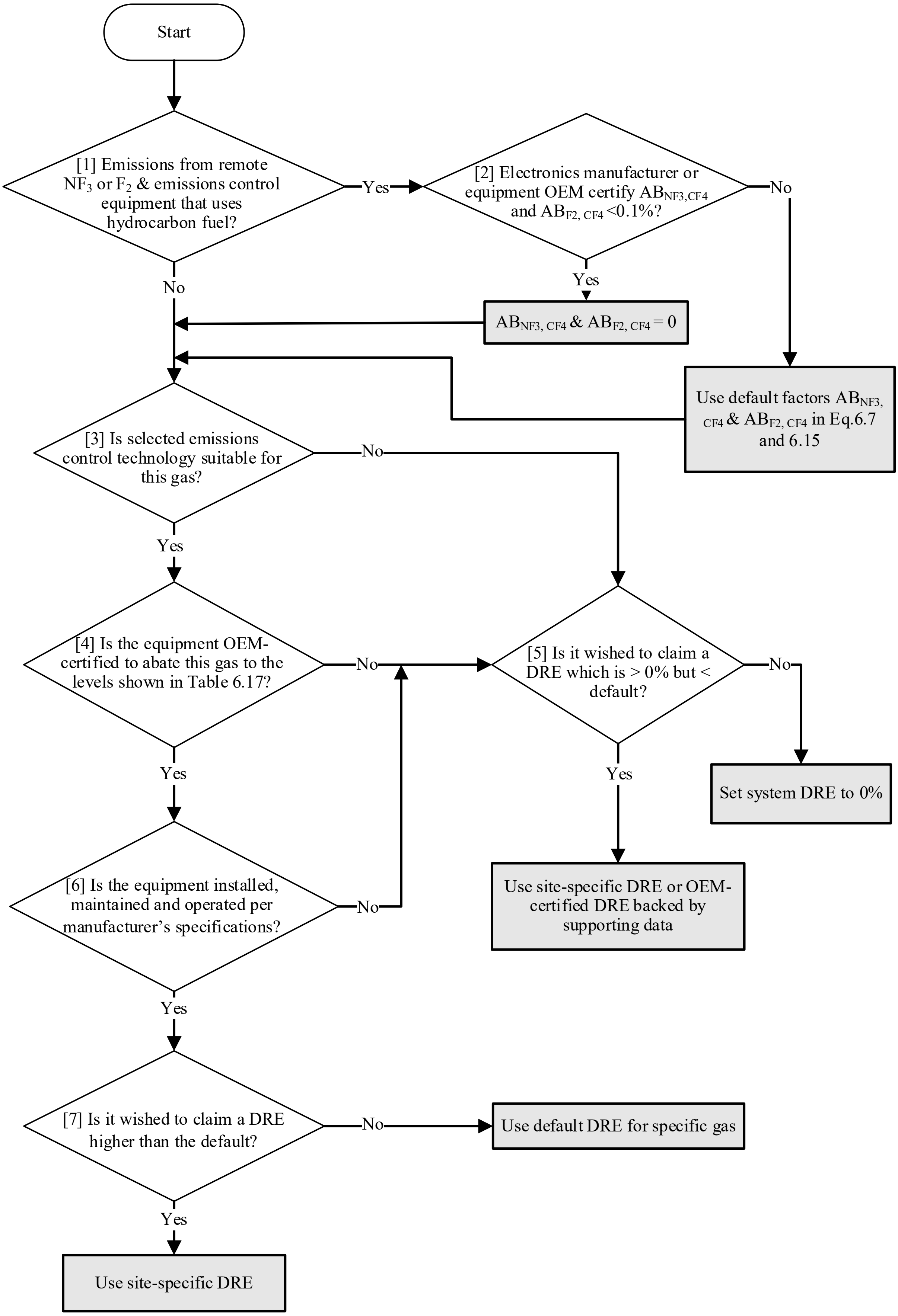
Hot-wet – This includes emissions control equipment described as "thermal wet" and indicates electrical heating followed by wet scrubbing. May also include a pre-wet scrubber.

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, air, hydrogen and/or oxygen as chemical reagents.

Combustion – This includes all configurations of fuel combustion and reaction zone design, water- or air-cooled, and dry or wet post-scrubbing.

New Technology – This is to account for the possibility of new emissions control technologies emerging that are not included in the categories above.

Figure 6.4 (New) Decision tree for process GHG emission control equipment default emission factors



Note: references to equipment in the above figure mean emission control equipment.

TABLE 6.17 (UPDATED)
TIER 2 DEFAULT DRE PARAMETERS FOR ELECTRONICS INDUSTRY PROCESS GAS EMISSIONS REDUCTION TECHNOLOGIES (DECIMAL FRACTION)

Process Gas	CF_4	C_2F_4	C_2F_6	C_3F_8	C_4F_6	c-C_4F_8	C_4F_8O (b)	C_5F_8 (a)	CHF_3	CH_2F_2	CH_3F	C_2HF_5 (a)	NF_3	SF_6	N_2O
DRE	0.89	0.98	0.98	0.99	0.98	0.98	0.98	0.98	0.98	0.99	0.99	0.98	0.95	0.96	0.60

Source: Data collected under the U.S. EPA Greenhouse Gas Reporting Rule (GHGRP, 40 U.S. Code of Federal Regulations (CFR) part 98; Subpart I) and survey of industrial facility and original equipment manufacturers (OEMs) data conducted by the authors of Chapter 6.

Notes: The average DRE values were derived from individual experimental DRE data points measured under actual or representative production conditions for each specific gas, using industry-accepted measurement protocols.

a) Insufficient data to determine a meaningful average value; analogue used instead (see below)

b) No data available to determine a meaningful average value; analogue used instead (see below)

c) C_4F_8 is used as the analogue for C_5F_8, and C_4F_8O as it has 4-carbon. C_2F_6 is used as the analogue for C_2HF_5 and C_2H_5F as it is linear 2-carbon. For future compounds, apply C_4F_8 for any cyclic compound, and follow linear analogue relative to C for those remaining.

6.2.2.2 FLUORINATED LIQUIDS

TABLE 6.18 (NEW)
TIER 1 DEFAULT EMISSION FACTORS FOR FLUORINATED LIQUIDS

Representative Fluorinated Liquids	Electronics Industry Sector		
	Semiconductor or MEMS heat transfer fluid applications during manufacturing (kg/m^2)	**Semiconductor or MEMS testing, packaging and soldering (kg/kpcs)**	**Display heat transfer fluid applications during manufacturing (kg/m^2)**
HFE-449sl	0.06	1×10^{-4}	0.00002
C_6F_{14}	0.07	3×10^{-5}	0.00004
PFPMIE	0.04	1×10^{-5}	0.00004

Note:

1. The default emission factors for semiconductor manufacturing from heat transfer fluid applications 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 facilities, 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 fluorinated liquids emitted was ten or more; these fluorinated liquids were sorted into three groups of chemically similar fluorinated liquids represented by the fluorinated liquids in the table. HFE-449sl is used to represent hydrofluoroethers; C_6F_{14} is used to represent fully fluorinated liquids manufactured by 3M™; and PFPMIE is used to represent fully fluorinated liquids manufactured by Solvay™.

2. Default emission factors for semiconductor testing, packaging, and soldering 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, Province of China.

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, Province of China. The number of fluorinated liquids emitted was seven; these fluorinated liquids were sorted into three groups of chemically similar fluorinated liquids represented by the fluorinated liquids in the table.

4. There is no heat transfer fluid Tier 1 default for PV and thus the only solution for estimating emissions of fluorinated liquids from these subsectors is the Tier 2 method.

5. There is no Tier 1 default for substrate cleaning and, therefore, the Tier 2 method should be used to estimate emissions from this source.

6.2.3 Choice of activity data

Activity data for the electronics industry consists of data on gas consumption 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 and Tier 3 methods, gas consumption data is necessary at the facility, substrate-size, process-type, or recipe levels, depending on the Tier. See the guidance regarding the calculation and apportioning of gas consumption under "Choice of Method." 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 Forecast (WFF) database, published quarterly by Semiconductor Equipment & Materials International (SEMI). 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, product type (including MEMS), and more. Other databases are available e.g., IC Insights, Gartner and VLSI.[17,18,19] Similarly, SEMI's 'Flat Panel Display Fabs on Disk' database provides an estimate of glass consumption for global TFT-Display manufacturing. IHS provide market data on the Solar/PV and display industries.[20]

Table 6.7 of the *2006 IPCC Guidelines* provided design capacity figures, but these values, which were estimated for 2003 through 2005, are no longer accurate. Table 6.7 is not updated in this *2019 Refinement* because the update would 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. Note that electronic devices manufacturing plants may not be operated at design capacities for sustained periods, such as a full year, as production typically 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. When country-specific capacity utilisation data are not available, the suggested capacity utilisation for semiconductor manufacturing is 80 percent, which should be used consistently for a time series of estimates. For display manufacturing, 2016 fab capacity utilisation ranged between 76 and 91 percent.[21] 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 to use for C_u (see Equation 6.1).

When estimating emissions during PV manufacture, one should account for the fraction of the industry that actually employs FCs (F_{PV} in Equation 6.1).

6.2.4 Completeness

Completeness for electronics manufacturing requires accounting for all fluorinated GHGs, N_2O (see section 6.1.1) and fluorinated liquids (see Table 6.5[22]) emitted from all emissions sources (see Table 6.1) at all facilities in all electronics manufacturing subsectors (see Table 6.2) in a country. Complete accounting of emissions from the electronics industry should be achievable in most countries because there are a limited number of companies and plants. Inventory compilers can contact national or international industry associations (e.g., the appropriate national or regional Semiconductor Industry Association) and/or FC suppliers to obtain contact information for electronics manufacturers in their countries. Note that national statistical databases usually do not provide detailed information about electronic devices manufacturing plants, and information about the manufacturing capacities and utilization of such plants is often considered confidential (e.g. actual surface area of substrate used or quantity of final product produced). Nevertheless, commercially-available databases provide facility-specific information

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[17] http://www.icinsights.com/services/global-wafer-capacity/

[18] https://www.gartner.com

[19] https://www.vlsiresearch.com/

[20] https://technology.ihs.com/

[21] https://electroiq.com/2016/11/display-panel-makers-increase-fab-utilization-rate-to-90-in-q4-2016/.

[22] Note that the list of fluorinated liquids in Table 6.5 is not exhaustive and that additional fluorinated liquids may be used. Thus, for completeness purposes, inventory compilers should check whether any fluorinated liquids other than those listed in Table 6.5 may be used at any particular facility

with production capacity estimates that can be used for the Tier 1 method (see section 6.2.3 “Choice of activity data”).

FC Consumption: Generally, electronics devices manufacturers will have good records of consumption of FC gases, N_2O, and fluorinated liquids. In compiling annual consumption of the relevant chemicals, completeness requires that the inventory of gases and fluorinated liquids account for the mass or volume of such chemicals stored in containers at the beginning and at the end of the year, acquisitions during the year through purchases and other transactions, but also transfers of chemicals and of equipment that may contain chemicals, including heels. Also, when apportioning gas consumption between process types, inventory compilers should ensure that the apportioning model does not omit or double count consumption for any particular process type.

By-Product Generation: Completeness also requires tracking emissions of all FC by-products that result from reactions of input gases with each other, with carbon-containing films, and with hydrocarbon fuels. See the guidance on these by-product emissions in section 6.2.1.1.

Fluorinated Liquids: A complete accounting of fluorinated liquids requires accounting for all uses of these liquids in all electronics subsectors in the country. As discussed in section 6.1.1, fluorinated liquids are used to control temperatures during manufacturing, to test devices, for soldering, and for cleaning of substrates and other parts. Because the Tier 1 default emission factors do not cover all of these uses in all subsectors, using the Tier 1 method for fluorinated liquids could affect the completeness of emissions estimates. Specifically, insufficient data was available to devise Tier 1 emission factors for the use of fluorinated liquids in cleaning substrates for all sub-sectors, as well as for heat transfer applications in the PV sub-sector, and for testing, packaging and soldering in the display and PV sub-sectors. Thus, for such applications and sub-sectors, inventory compilers should check whether fluorinated liquids are used at any particular facility, and, to ensure completeness, use only the Tier 2 method in such cases.

Other products, research and development (R&D) and tool commissioning activities: Inventory compilers should be aware that new guidance was added to Volume 3, Chapter 8 of the *2019 Refinement* to account for fluorochemicals emissions used to waterproof electronic circuits. As mentioned above, new products and processes may be introduced from time to time during the course of electronic devices manufacturing, and *good practice* for this industry is to incorporate a mechanism that accounts for reporting the introduction of new products and processes that may affect emissions estimates, and for periodically reporting newly measured emission factors to the IPCC emission factors database (EFDB). Note that it is *good practice* to include gas purchases in support of R&D and tool commissioning activities in the consumption figures used for a particular facility.

6.2.5 Developing a consistent time series

Use of FCs and N_2O by the semiconductor industry began in the late 1970s and accelerated significantly beginning in the early 1990s. Determining a base year emissions level may present difficulties because few data are available for emissions occurring before 1995. If historical emissions estimates were based on simple assumptions (e.g., use equals emissions), then these estimates could be improved by applying the methods described above. Emission factors for the electronics industry have also been revised since the publication of the *2006 IPCC Guidelines* and the consistency of the time series could be improved by applying the revised emission factors to the full time series. The 2019 Tier 2a, 2b or 2c emission factors can be applied to the historical emissions previously calculated with the 2006 Tier 2a or Tier 2b emission factors. For the semiconductor sub-sector, if the wafer size manufactured is not known, 2019 Tier 2a emission factors should be applied to data from 2005 or later. Due to the prevalence of 200 mm or smaller wafer sizes prior to 2005, the 2019 Tier 2b emission factors for 200 mm should be applied to data from 2004 or earlier instead of the Tier 2a emission factors. If historical data are not available to permit use of a Tier 3 or 2 methods, then the Tier 1 method using default emission parameters can be used retrospectively. In this case, it is *good practice* to use the Tier 1 factors from the *2006 IPCC Guidelines* for years through 2010. For 2011 and the following years, it is *good practice* to use the Tier 1 factors from the *2019 Refinement* for most sub-sectors; however, for the semiconductor sub-sector, in cases where it is known that the wafer size manufactured is 200 mm or smaller, it is *good practice* to continue to use the Tier 1 factors from the *2006 IPCC Guidelines*. Both Tier 1 and Tier 2 could then be applied simultaneously for the years in which more data become available to provide a comparison for purposes of splicing the results of the Tier 1 and Tier 2 methods. This should be done according to the guidance provided in Volume 1, Chapter 5.

In order to ensure a consistent emissions record over time, an inventory compiler should recalculate FC and N_2O emissions for all years reported whenever emissions calculation procedures are changed (e.g., if an inventory compiler changes from the use of default values to actual values determined at the plant level). If plant-specific data are not available for all years in the time series, the inventory compiler will need to consider how current plant data can be used to recalculate emissions for these years. It may be possible to apply current facility-specific emission parameters to sales data from previous years, provided that facility operations have not changed substantially. Such a recalculation is required to ensure that any changes in emission trends are real and not an artefact of changes in procedure. If substantial changes have occurred at a facility which prevent full recalculation or new variables are introduced in the equations such as emissions control equipment uptime or apportioning abated gas use to process type, the inventory compiler can apply both the previously used and the new method for at least one year and preferably more to provide a comparison. If the trends observed using this overlap splicing technique are not consistent then use of an alternate technique provided in Volume 1, Chapter 5 should be implemented.

6.3 UNCERTAINTY ASSESSMENT

6.3.1 Emission factor uncertainties

As discussed in the Choice of Method section, the Tier 1 emission factors are expected to be highly uncertain because they do not account for the identities and quantities of the gases actually consumed, for the process types in which those gases are used, for wafer size (for semiconductors), or for the use of emission control systems. A quantitative estimate of the uncertainty of the Tier 1 emission factors (EFs) could not be developed based on the data available, but gas consumption is known to vary widely by device type (e.g., memory vs. logic for semiconductor manufacturing), and gas-specific EFs are known to vary widely by process type, by wafer size and by the fraction of emissions abated. Thus, the Tier 1 method is the least accurate estimation method and should be used only in cases where facility-specific data are not available.

The relative uncertainties at the 95 percent confidence level, estimated for each emission factor of the Tier 2b and 2c methods, are shown in Tables 6.19, and 6.20 for semiconductor manufacturing. It was not possible to estimate the uncertainty of the Tier 2a emission factors for the semiconductor sub-sector and of the Tier 2c emission factors for the display sub-sector due to lack of data. To estimate uncertainties, the relative standard deviations for each Tier 2c entry were first calculated across all experimental data points (measured utilization efficiencies and by-product emission factors) for each particular gas i, process type, and wafer size. The relative standard deviations were then rounded to one significant figure and doubled to estimate uncertainties at the 95 percent confidence level. The same method was used for the Tier 2b entries for each gas and wafer size. The large uncertainties of Tier 2 emission factors are due to the wide distributions of individual experimental emission factors, which depend on process conditions and on the design of the process chambers. Because process conditions such as gas flows, pressure, temperature, or plasma power can vary widely for a particular gas and process chamber design, the utilization efficiencies or by-product emission factors can also significantly change from one process recipe to another, even within a particular process type. Although electronic devices manufacturers can typically run hundreds or even thousands of different recipes (with differing process conditions and manufacturing tool types) – providing an averaging effect over all recipe-specific emission factors –, actual emission factors (for any particular facility) may nevertheless differ from the Tier 2c, 2b, or 2a default emission factors. Because the Tier 2a and Tier 2b methods provide lower resolution than the Tier 2c method (Tier 2a emission factors are only disaggregated by input gas i, and Tier 2b emission factors are only disaggregated by input gas and by wafer size), the overall uncertainty of the Tier 2a and 2b methods can be expected to be higher than for the Tier 2c method.

The impact of the Tier 2 emission factors' uncertainties on the overall emissions estimate for a particular electronic device manufacturing facility can be estimated by combining the probability distribution functions (PDFs) of the emission factors. Approaches to combine uncertainties include the propagation of error method and Monte Carlo simulations (see Volume 1, Chapter 3 of the *2019 Refinement*). For electronic devices manufacturing, the Monte Carlo approach is suggested because the propagation of error method theoretically requires that the standard deviation divided by the mean value of a variable is less than 0.3, which is often not the case for Tier 2 emission factors (Id.).

Using the Tier 3a method can help significantly reduce reporting uncertainties, even in the case of a hybrid method when a partial Tier 3a method is used in combination with the Tier 2c method. This is because the standard deviations of emission factors for a specific recipe or for a family of similar recipes (Tier 3a factors) can be much lower than those of default Tier 2c factors. Indeed, when running a particular recipe, process conditions such as gas flows, temperature, pressure, or plasma power are tightly controlled, and the wafer-to-wafer variability of emission factors is typically less than 5 percent in terms of relative standard deviations. When using Monte Carlo simulations to estimate the uncertainty of combined Tier 2c / Tier 3a emissions estimates for a particular facility, reporters should use a PDF describing the distribution functions of each Tier 2b or Tier 3a factor and combine such functions to determine the impact of the individual EF uncertainties on the uncertainty of the overall emissions estimate. Normal, lognormal, or other appropriate functions should be used to describe the PDFs of the variables. Then, suitable PDFs should be used to describe the variations of activity data (e.g. heel, input gas consumption, emissions control equipment efficiency – see Section 6.3.2) and such PDFs should be combined with those of the emission factors to estimate the uncertainty of the total emissions calculations.

TABLE 6.19 (UPDATED)
ESTIMATES OF RELATIVE UNCERTAINTIES (%) OF TIER 2B EMISSION FACTORS FOR SEMICONDUCTOR MANUFACTURING, 95 PERCENT CONFIDENCE INTERVALS.

Process Gas	CF_4	C_2F_6	C_3F_8	C_3F_8 Remote	C_4F_6	c-C_4F_8	C_4F_8O	C_5F_8	CHF_3	CH_2F_2	CH_3F	C_2HF_5	NF_3 Remote	NF_3	SF_6	N_2O TFD	N_2O Other	COF_2	F_2
≤200 mm wafer size																			
($1-U_i$)	†	40	†	NA	200	†	†	†	100	160	†	100	200	150	†	NA	NA	NA	NA
B_{CF4}	NA	120	†	NA	200	†	†	NA	80	140	NA	100	180	†	†	NA	NA	NA	NA
B_{C2F6}	400	NA	NA	NA	400	†	†	†	200	120	†	140	NA	†	†	NA	NA	NA	NA
B_{C3F8}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C5F8}	†	NA	NA	NA	NA	†	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{CHF3}	120	†	NA	NA	†	†	NA	†	NA	†	NA	NA	NA	NA	†	NA	NA	NA	NA
300 mm wafer size																			
($1-U_i$)	60	†	†	†	200	140	NA	180	120	200	140	NA	400	200	140	120	NA	NA	NA
B_{CF4}	NA	†	†	NA	400	200	NA	160	200	200	200	NA	600	†	400	NA	NA	NA	NA
B_{C2F6}	200	NA	†	NA	400	160	NA	200	400	200	200	NA	NA	400	200	NA	NA	NA	NA
B_{C3F8}	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F6}	†	NA	NA	NA	NA	†	NA	NA	†	NA	40	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F8}	400	NA	NA	NA	†	NA	NA	NA	†	†	†	NA	NA	NA	NA	NA	NA	NA	NA
B_{CH3F}	200	NA	†	NA	†	†	NA	NA	400	†	NA	NA	NA	†	†	NA	NA	NA	NA
B_{CH2F2}	†	NA	NA	NA	†	†	NA	NA	†	NA	†	NA	NA	†	†	NA	NA	NA	NA
B_{CHF3}	200	NA	†	NA	400	200	NA	400	NA	180	200	NA	NA	400	†	NA	NA	NA	NA

† Insufficient data was available to calculate uncertainty.

Table 6.20 (Updated)
Default estimates of relative uncertainties (%) of Tier 2c emission factors for semiconductor manufacturing (≤200 mm), 95 percent confidence intervals

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_4F_6**	**$c\text{-}C_4F_8$**	**C_4F_8O**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**C_2HF_5**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O Other**	**COF_2**	**F_2**
Etching or Wafer Cleaning (EWC)																	
$(1-U_i)$	40	60	NA	200	140	NA	†	100	160	†	100	140	100	NA	NA	NA	NA
B_{CF4}	NA	180	NA	200	200	NA	NA	80	140	NA	100	†	†	NA	NA	NA	NA
B_{C2F6}	400	NA	NA	400	400	NA	†	200	120	†	140	†	†	NA	NA	NA	NA
B_{C5F8}	†	NA	NA	NA	†	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{CHF3}	120	†	NA	†	†	NA	†	NA	†	NA	NA	NA	†	NA	NA	NA	NA
Remote Plasma Cleaning (RPC)																	
$(1-U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	200	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	180	NA	NA	NA	NA	NA
In-situ Plasma Cleaning (IPC)																	
$(1-U_i)$	†	40	†	NA	†	†	NA	NA	NA	NA	NA	180	NA	NA	NA	NA	NA
B_{CF4}	NA	120	†	NA	†	†	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA
B_{C2F6}	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Thin Film Deposition (TFD)																	
$(1-U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA
Other																	
$(1-U_i)$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA

† Insufficient data was available to calculate uncertainty.

Table 6.21 (Updated)
Default estimates of relative uncertainties (%) of Tier 2c emission factors for semiconductor manufacturing (300 mm), 95 percent confidence intervals

Process Gas	CF_4	C_2F_6	C_3F_8	C_4F_6	$c\text{-}C_4F_8$	C_5F_8	CHF_3	CH_2F_2	CH_3F	NF_3	SF_6	N_2O TFD	N_2O Other	COF_2	F_2
Etching and Wafer Cleaning (EWC)															
(1-U_i)	60	†	†	200	140	180	120	200	140	180	140	NA	NA	NM	NM
B_{CF4}	NA	†	†	400	200	160	200	200	200	200	400	NA	NA	NM	NM
B_{C2F6}	200	NA	†	400	160	200	400	200	200	200	200	NA	NA	NM	NM
B_{C3F8}	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_{C4F6}	†	NA	NA	NA	†	NA	†	NA	40	NA	NA	NA	NA	NA	NA
B_{C4F8}	400	NA	NA	†	NA	NA	†	†	†	NA	NA	NA	NA	NA	NA
B_{CH3F}	200	NA	†	†	†	NA	400	†	NA	†	†	NA	NA	NA	NA
B_{CH2F2}	†	NA	NA	†	†	NA	†	NA	†	†	†	NA	NA	NA	NA
B_{CHF3}	200	NA	†	400	200	400	NA	180	200	200	†	NA	NA	NA	NA
Remote Plasma Cleaning (RPC)															
(1-U_i)	NA	NA	†	NA	NA	NA	NA	NA	NA	400	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	600	NA	NA	NA	NA	NA
In-situ Plasma Cleaning (IPC)															
(1-U_i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	100	NA	NA	NA	NA	NA
B_{CF4}	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA	NA	NA	NA
In-situ Thermal Cleaning (ITC)															
(1-U_i)	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
TFD															
(1-U_i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	120	NA	NA	NA

TABLE 6.21 (UPDATED) (CONTINUED)
DEFAULT ESTIMATES OF RELATIVE UNCERTAINTIES (%) OF TIER 2C EMISSION FACTORS FOR SEMICONDUCTOR MANUFACTURING (300 MM), 95 PERCENT CONFIDENCE INTERVALS

Process Gas	**CF_4**	**C_2F_6**	**C_3F_8**	**C_4F_6**	**c-C_4F_8**	**C_5F_8**	**CHF_3**	**CH_2F_2**	**CH_3F**	**NF_3**	**SF_6**	**N_2O TFD**	**N_2O Other**	**COF_2**	**F_2**
Other															
(1-U_i)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	†	NA	NA

† Insufficient data was available to calculate uncertainty.

6.3.2 Activity data uncertainty

Activity data uncertainty originates from multiple variables and particular attention should be taken to minimize the uncertainty and the potential bias of the measurements or of the models used to estimate activity data.

For the Tier 1 method, the unit of activity is annual production, preferably measured as the surface area of substrate used during the production of electronic devices. Because annual production may be considered confidential by electronic devices manufacturers, it may be difficult to accurately estimate production at the facility level, and, consequently, at the country level. Further, if annual production is calculated as the product of annual plants' manufacturing capacity and of utilization efficiencies provided by secondary sources (i.e. commercial databases), additional sources of uncertainties can be introduced. This is because manufacturing capacity figures available in commercial databases may be inaccurate, and because capacity utilization figures are often averaged for the global industry or may only be available for certain types of electronic products (e.g. memory, logic, discrete devices). Therefore, inventory compilers should keep in mind that annual production figures calculated from secondary sources may not accurately represent country-specific activities. Because of such limitations, the Tier 1 method should only be used in cases where facility-specific data are not available.

For the Tier 2 and Tier 3 methods, gas consumption constitutes the principal unit of activity to estimate emissions and can therefore be a major potential source of uncertainty and errors. Gas consumption can be either measured or estimated from data on gas purchases, and requires knowledge of the heel, the unused gas returned to gas suppliers in the shipping containers. Using facility-specific heel measurements or accurate heel modelling as opposed to using the default heel value of 0.1 can help reduce uncertainty and error. Another major source of uncertainty and potential errors in activity data is related to gas consumption apportioning, where consumption may need to be apportioned by wafer size (Tier 2b), by specific process type (Tier 2c and, to a limited extent, Tiers 2a and 2b), and/or by specific recipes or families of similar recipes (Tier 3a).

To minimize apportioning uncertainty and increase accuracy, it is *good practice* to implement a gas consumption monitoring system using direct measurement to apportion gas use at the process type-, stack system- or facility-level as appropriate. This can be achieved by various methods including monitoring and integrating the signal of MFCs and using weigh scales; however, it is noted that measurement to specific tools or processes may not be feasible.

Finally, activity data related to the effective use of emissions control systems should be accurately assessed as part of any Tier 2 or Tier 3 method to minimize uncertainties and potential errors. In particular, accurately estimating the fraction of gases used or produced in processes with emissions control technologies (a_i, a_k), the average uptime of emissions control systems (UT), and the overall reduction of input gases and by-products (D_i, $D_{k,i}$) is essential in producing reliable emissions estimates. With respect to the calculation of a_i and $a_{k,i}$ in the Tier 2a or Tier 2b estimates, using default gamma values ($\gamma_{i,p}$ and $\gamma_{k,i,p}$) to estimate the ratio of the uncontrolled emissions per tool of input gases 'i' or by-products 'k' from thin film deposition tools to the uncontrolled emissions per tool of input gases 'i' or by-products 'k' from etch and wafer cleaning or other tools, introduces a significant source of uncertainty and potential errors (see Table 6.22). Thus, to reduce uncertainty, avoiding the use of gamma default values by apportioning gas consumption by process type (i.e. using the Tier 2c method rather than the Tier 2a or Tier 2b methods) is encouraged.

For fluorinated liquids, the uncertainty of the Tier 2 method will depend on the accuracy of the inventory method. Accurately tracking the number of fluorinated liquid containers at the beginning and at the end of the year, as well as the total nameplate capacity of equipment that uses fluorinated liquids and that is newly installed in or removed from the fab during the reporting year will ensure that uncertainties are minimized and that fluorinated liquid emissions estimates are reliable.

As described in section 6.3.1, Monte Carlo simulations can be used to estimate the impact of uncertainties in activity data by measuring or modelling the probabilities of distributions functions (PDF) of uncertain activity data, and by combining the PDFs of activity-related variables and the PDFs of emission factors.

TABLE 6.22 (NEW)
TIER 2A, 2B AND 3B METHODS – ESTIMATES OF RELATIVE UNCERTAINTIES (%) FOR $\gamma_{I,P}$ AND $\gamma_{K,I,P}$ (SEMICONDUCTOR AND MEMS MANUFACTURING UNDER CERTAIN CONDITIONS), 95 PERCENT CONFIDENCE INTERVALS

Tier, input gas (γi,p) vs. byproduct (γk,i,p), and wafer size	**CF4 (IPC or ITC) / EWC**	**C2F6 IPC / EWC**	**c-C4F8 IPC / EWC**	**NF3 (IPC or ITC) / EWC**	**SF6 IPC / EWC**	**NF3 RPC / EWC**	**CF4 RPC / EWC**	**C3F8 RPC / EWC**	**N2O TFD / other**
Tier 2a*									
$\gamma_{i,p}$	240†	260	200	180†	340	▨	▨	▨	▨
$\gamma_{CF4,i,p}$	NA	>260	>200	>180	>340	▨	▨	▨	▨
$\gamma_{C2F6,i,p}$	NA	NA	NA	NA	>340	▨	▨	▨	▨
Tier 2b									
$\gamma_{i,p}$ (≤200 mm wafer size)	240†	260	200	180†	340	▨	▨	▨	▨
$\gamma_{CF4,i,p}$ (≤200 mm wafer size)	NA	>260	>200	>180	>340	▨	▨	▨	▨
$\gamma_{C2F6,i,p}$ (≤200 mm wafer size)	NA	NA	NA	NA	>340	▨	▨	▨	▨
$\gamma_{i,p}$ (300 mm wafer size)	NM	NM	NM	280†	NM	▨	▨	▨	▨
$\gamma_{CF4,i,p}$ (300 mm wafer size)	NA	NA	NA	>280	NA	▨	▨	▨	▨
Tier 3b									
$\gamma_{i,p}$ (both ≤200 mm and 300 mm wafer size)	240†	260	200	180†	340	320	NM	NM	400
$\gamma_{CF4,i,p}$ (both ≤200 mm and 300 mm wafer size)	NA	>260	>200	>180	>340	>320	NA	NA	NA
$\gamma_{C2F6,i,p}$ (both ≤200 mm and 300 mm wafer size)	NA	NA	NA	NA	>340	NA	NA	NA	NA
$\gamma_{i,p}$ (≤200 mm wafer size)	240†	260	200	180†	340	160	NM	NM	160
$\gamma_{CF4,i,p}$ (≤200 mm wafer size)	NA	>260	>200	>180	>340	>160	NM	NA	NA
$\gamma_{C2F6,i,p}$ (≤200 mm wafer size)	NA	NA	NA	NA	>340	NA	NA	NA	NA
$\gamma_{i,p}$ (300 mm wafer size)	NM	NM	NM	280†	NM	320	NM	NM	400
$\gamma_{CF4,i,p}$ (300 mm wafer size)	NA	NA	NA	>280	NA	>320	NA	NA	NA

Source: Survey of industrial facility data conducted by the authors of Chapter 6.

*The uncertainties for the Tier 2a gamma weighting factors are estimated using the higher of the uncertainties for the gamma factors for 200- and 300-mm wafer manufacturing for that input gas and process type combination.

† The gamma values for (IPC or ITC)/EWC for 200 mm, and their corresponding uncertainties, were developed based on IPC only, and the values (and corresponding uncertainties) for 300 mm were developed based on the total emissions and tool count from ITC and IPC. Gamma is assigned based on analogy due to similar emission factors for IPC and ITC, where known, for the same gas and wafer size. For cases where no gamma has been measured and a general default gamma factor of 10 is used (see footnote to Table 6.8), the inventory compiler may assume an uncertainty of 500 percent.

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

6.4.1 Quality Assurance / Quality Control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Volume 1, Chapter 6 of the *2019 Refinement*, and an expert review of the emissions estimates. Additional quality control checks as outlined in Volume 1 and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory compilers are encouraged to use higher tier QA/QC for *key categories* as identified in Volume 1, Chapter 4.

Additional general guidance for higher tier QA/QC procedures is also included in Volume 1, Chapter 6 of the *2019 Refinement*. Due to the highly competitive nature of the electronics industry, provisions for handling confidential business information should be incorporated into the verification process. Methods used should be documented, and a periodic audit of the measurement and calculation of data should be considered. A QA audit of the processes and procedures should also be considered.

It should be noted that comparing Tier 2 and Tier 3a (bottom-up) estimates with Tier 3b (top-down) estimates for representative facilities could help assess the accuracy (or inaccuracy) of the various methods. The Tier 2 and Tier 3a methods are deemed 'bottom-up' approaches because they are based upon consumption at the input of the process tools, while the Tier 3b method is considered a 'top-down' approach as it is based on measuring stack-specific (end of pipe) emission factors. Thus, comparing Tier 2 (or preferably Tier 3a) estimates with Tier 3b estimates would help assess whether biases may exist between top-down and bottom-up estimates.

6.4.2 Reporting and Documentation

Care should be taken not to include emissions of HFCs used as ODS substitutes with those used in electronic devices manufacturing. It is *good practice* to document and archive all information required to produce facility-level and national emissions inventory estimates as outlined in Volume 1, Section 6.11 of the *2019 Refinement*. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and that steps in their calculation may be retraced.

Efforts to increase transparency should take into account the protection of confidential business information related to specific gas use. Country-level aggregation of gas-specific emissions data should protect this information in countries with three or more manufacturers. Table 6.23 (Information Necessary for Full Transparency of Estimates of Emissions from Electronics Manufacturing), shows the supporting information necessary for full transparency in reported emissions estimates.

Good practice for Tier 3a and 3b is to document the development of company-specific emission factors, and to explain deviations from default values. Given confidentiality concerns, inventory compilers may wish to aggregate this information across manufacturers. In cases where manufacturers in a country have reported different emission or conversion factors for a given fluorinated compound or N_2O and for specific recipes or families of similar recipes, inventory compilers may provide the range of factors reported and used.

TABLE 6.23 (NEW)
INFORMATION NECESSARY FOR FULL TRANSPARENCY OF ESTIMATES OF EMISSIONS FROM ELECTRONICS MANUFACTURING

Data	Tier 1 (Gaseous and Liquid FCs)	Tier 2 (Liquid FCs)	Tier 2a	Tier 2b	Tier 2c	Tier 3a	Tier 3b
Emissions by FC and electronics subsector	X						
Annual production, as measured by the surface area of substrate used during the production of electronic devices, including test substrates	X						
Fraction of PV manufacturing capacity that uses FC gases	X						
For gaseous FCs, emissions by FC, electronics subsector, process type, wafer size (if relevant), and input gas vs. by-product. For liquid FCs, emissions by FC and electronics subsector.		X	X	X	X	X	X
Inventories of input gases and heat transfer fluids (inventories of containers at the beginning and end of the year, acquisitions, transfers, and (for fluorinated liquids only) nameplate capacity of equipment added or removed during the reporting year		X	X	X	X	X	X
Sizes, types, and total number of different sized containers in the facility			X	X	X	X	X
Types and densities of fluorinated liquids used in the facility		X					
Heel values used for all gases			X	X	X	X	X
Documentation describing the facility-specific apportioning model and demonstration of its accuracy			X	X	X	X	X
Consumption data for all input gases (and, except for the Tier 3b method, apportioning factors) as a function of wafer size and/or process type, as appropriate			X	X	X	X	X
Ratio of process TFD chambers running carbon containing films to total number of TFD chambers			X	X	X	X	

TABLE 6.23 (NEW) (CONTINUED)
INFORMATION NECESSARY FOR FULL TRANSPARENCY OF ESTIMATES OF EMISSIONS FROM ELECTRONICS MANUFACTURING

Data	Tier 1	Tier 2 (Fluorinated liquids)	Tier 2a	Tier 2b	Tier 2c	Tier 3a	Tier 3b
Numbers of EWC and TFD tools equipped with suitable emissions control technologies			X	X	X	X	X
Total numbers of EWC and TFD tools			X	X	X	X	X
Mass fractions of gases and by-products exhausted from tools with emissions control technologies, by process type or facility, as appropriate			X	X	X	X	X
Number and types (manufacturer, model number, technology) of emissions control systems installed in the facility, by process type or facility, as appropriate			X	X	X	X	X
Documentation describing the facility’s procedure to estimate the average uptime of emissions control systems			X	X	X	X	X
Documentation describing the emissions control systems’ interlock scheme or the use of back-up emissions control systems (if applicable)			X	X	X	X	X
Average uptime factor of all emissions control systems connected to process tools, by process type or facility, as appropriate			X	X	X	X	X
Overall reduction of input gases and by-products by process type or facility, as appropriate			X	X	X	X	X
Ratio of emissions control systems certified not to form CF_4 within emissions control systems to total number of emissions control systems in the facility			X	X	X	X	
Certifications by original equipment manufacturers (OEMs) that emissions control systems are designed to abate the relevant gases and that the default DREs can be met in the worst-case scenario for the facility			X	X	X	X	X
Documentation showing that emissions control equipment is maintained and operated per manufacturers’ specifications			X	X	X	X	X
Measured (facility-specific) destruction removal efficiencies (when default values are not used), and actual measurement reports, including a description of the experimental conditions			X	X	X	X	X

TABLE 6.23 (NEW) (CONTINUED)
INFORMATION NECESSARY FOR FULL TRANSPARENCY OF ESTIMATES OF EMISSIONS FROM ELECTRONICS MANUFACTURING

Data	Tier 1	Tier 2 (Fluorinated liquids)	Tier 2a	Tier 2b	Tier 2c	Tier 3a	Tier 3b
Measured (facility-specific) utilization efficiencies and by-products emission factors, as well as actual measurement reports, including a description of the experimental conditions.						X	X
Flow rates of the stack systems							X

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CHAPTER 7

EMISSIONS OF FLUORINATED SUBSTITUTES FOR OZONE DEPLETING SUBSTANCES

Authors

Kathrine Loe Bjønness (Norway), Tomas Gustafsson (Sweden), Junichi Ishikawa (Japan) and Michela Maione (Italy)

Contributing Authors

Barbara Gschrey (Germany), Tetsuji Okada (Japan), Roberto de Aguiar Peixoto (Brazil) and Winfried Schwarz (Germany)

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7 EMISSIONS OF FLUORINATED SUSBSTITUTES FOR OZONE DEPLETING SUBSTANCES

Users are expected to go to Mapping Tables in Annex 5, before reading this chapter. This is required to correctly understand both the refinements made and how the elements in this chapter relate to the corresponding chapter in the 2006 IPCC Guidelines.

7.1 INTRODUCTION

7.1.1 Chemicals and relevant application areas covered

Hydrofluorocarbons (HFCs) and, to a very limited extent, perfluorocarbons (PFCs), are serving as alternatives to ozone depleting substances (ODS) being phased out under the Montreal Protocol. Current and expected application areas of HFCs and PFCs include (IPCC/TEAP, 2005 and UNEP-TEAP 2016a/b):

- refrigeration and air conditioning;
- fire suppression and explosion protection;
- aerosols;
- solvent cleaning;
- foam blowing; and
- other applications[1].

These major groupings of current and expected usage are referred to in this chapter as *applications* within the ODS substitutes category. This introduction (Section 7.1) provides a general framework for estimating emissions from ODS substitutes, and subsequent sections (Sections 7.2 through 7.7) provide more specialised guidance on the individual applications introduced above. Some of these applications themselves encompass products or uses with diverse emission characteristics, and countries will produce more rigorous estimates if they account for this diversity through the adoption of disaggregated assessments (higher tier). Additionally, the use of HFCs and PFCs in some applications, specifically rigid foam（typically closed-cell foam), refrigeration and fire suppression, can lead to the development of long-lived *banks*[2] of material. The emission patterns from these uses can be particularly complex and methods employing disaggregated data sets are essential to generate accurate emissions estimates. Other applications, such as aerosols and solvent cleaning may have short-term inventories of stock but, in the context of emission estimation, can still be considered as sources of prompt emission. This statement also applies to flexible foams（typically open-cell foam).

HFCs are chemicals containing only hydrogen, carbon, and fluorine. Prior to the Montreal Protocol and the phase-out of various ODS, the only HFCs produced were HFC-152a, which is a component of the refrigerant blend R-500, and HFC-23, a low temperature refrigerant which is a by-product of HCFC-22[3] production. HFC-134a entered production in 1991 and a variety of other HFCs have since been introduced and are now being used as ODS substitutes (IPCC/TEAP, 2005) among other applications. When collecting data on HFC and PFC consumption for reporting purposes, care needs to be taken to include those HFCs in blends, but, at the same time, to avoid including those components of a blend which are not required to be reported (e.g., CFCs and HCFCs).

HFCs and PFCs have high global warming potentials (GWPs) and, in the case of PFCs, long atmospheric residence times. Table 7.1 gives an overview of the most important HFCs and PFCs, including their main

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[1] HFCs and PFCs may also be used as ODS substitutes in sterilisation equipment, for tobacco expansion applications, and as solvents in the manufacture of adhesives, coating and inks.

[2] A bank is in this context the amount of ODS-substitutes stored in products (applications) in a country.

[3] HCFCs - hydrochlorofluorocarbons.

application areas. The various HFCs and PFCs have very different potencies as greenhouse gases. PFCs have particularly high GWPs regardless of the integrated time horizon adopted because of their long atmospheric lifetimes. The consumption patterns relating to individual gases must be known, therefore, or estimated with reasonable accuracy, to achieve useful assessments for the contribution to global warming from emissions of these groups of chemicals.

As CFCs, halons, carbon tetrachloride, methyl chloroform, and, ultimately, HCFCs are being finally phased out[4], HFCs are being selectively used as replacements. PFCs are also being used, but only to a limited extent. HFC use is expected to continue to grow, at least in the short term (UNEP-TEAP, 2016a/b).

Since the *2006 IPCC Guidelines* were finalized, a major change has occurred in the policy framework regulating HFCs. Formerly, HFCs, which do not directly deplete O_3, were not regulated under the Montreal Protocol. However, during the 28th meeting of the parties (MOP28) held in Kigali (Rwanda) in October 2016, 197 countries adopted an amendment to phase down HFCs. The parties committed to cut the GWP-weighted production and consumption of HFCs by more than 80 percent over the next 30 years. Developed countries will begin reducing HFC consumption in 2019 and developing countries will follow with a freeze of HFC consumption levels between 2024 and 2028. A small group including the world's hottest countries (India, Pakistan, Iran, Saudi Arabia and Kuwait) will freeze HFC use by 2028. These production and consumption limits are expected to drive changes in the quantities and types of HFCs used in ODS substitute applications. To ensure that their HFC emissions inventories remain accurate, inventory compilers should familiarize themselves with the HFC limits in their countries and plan to gather data on the associated changes in HFC use and emissions.

TABLE 7.1 (UPDATED)
MAIN APPLICATION AREAS FOR HFCs AND PFCs AS ODS SUBSTITUTES[1]

Chemical	Refrigeration and Air Conditioning	Fire Suppression and Explosion Protection	Aerosols		Solvent Cleaning	Foam Blowing	Other Applications[2]
			Propellants	Solvents			
HFC-23	X	X					
HFC-32	X						
HFC-125	X	X					
HFC-134a	X	X	X			X	X
HFC-143a	X						
HFC-152a	X		X			X	
HFC-227ea	X	X	X			X	X
HFC-236fa	X	X					
HFC-245fa	X			X		X	
HFC-365mfc				X	X	X	
HFC-43-10mee				X	X		
PFC-14[3] (CF_4)		X					
PFC-116 (C_2F_6)							X
PFC-218 (C_3F_8)							
PFC-31-10 (C_4F_{10})		X					
PFC-51-14[4] (C_6F_{14})					X		

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[4] Refer to http://hq.unep.org/ozone/ for the phaseout schedules dictated under the Montreal Protocol.

TABLE 7.1 (UPDATED) (CONTINUED)
MAIN APPLICATION AREAS FOR HFCS AND PFCS AS ODS SUBSTITUTES1

Source: IPCC (1996), IPCC (2001), IPCC/TEAP (2005), UNEP-TEAP (2016a)

[1] Several applications use HFCs and PFCs as components of blends. The other components of these blends are sometimes ODSs and/or non-greenhouse gases. Several HFCs, PFCs and blends are sold under various trade names; only generic designations are used in this chapter.

[2] Other applications include sterilisation equipment, tobacco expansion applications, plasma etching of electronic chips (PFC-116) and as solvents in the manufacture of adhesive coatings and inks (Kroeze, 1995; U.S. EPA, 1992a). Note that although the use of PFCs for plasma etching is mentioned as an example in footnotes 2 and 3 to this table, the methodology for estimating emissions is described in Chapter 6 of Volume 3: Electronics Industry Emissions.

[3] PFC-14 (chemically CF_4) is used as a minor component of a proprietary blend. Its main use is for semiconductor etching.

[4] PFC-51-14 is an inert material, which has little or nil ability to dissolve soils. It can be used as a carrier for other solvents or to dissolve and deposit disk drive lubricants. PFCs are also used to test that sealed components are hermetically sealed.

7.1.2 General methodological issues for all ODS substitute applications

7.1.2.1 OVERVIEW OF ODS SUBSTITUTE ISSUES

No refinement.

7.1.2.2 CHOICE OF METHOD

As already described, emissions of ODS substitutes can be estimated in a variety of ways with varying degrees of complexity and data intensity. This chapter provides less data-intensive Tier 1 methods, typically based on low levels of disaggregation, and more data-intensive Tier 2 methods, which require higher levels of disaggregation. A third Tier (Tier 3), based on actual monitoring and measurement of emissions from point sources, is technically possible for specific sub-applications but this is rarely, if ever, employed for ODS substitutes, because the individual point sources are widely disparate. Accordingly, Tier 3 methods are not addressed further in this chapter.

TIER 1 METHODS

Tier 1 methods tend to be less data-intensive and less complex than Tier 2 because emission estimates are usually carried out at the application level rather than for individual products or equipment types. However, the approaches proposed vary considerably depending on the characteristics of the specific application. There can be Tier 1a approaches, Tier 1b approaches and, sometimes, combinations of the two (Tier 1 a/b). The latter is often the case where data are in short supply. Effectively, the output of a Tier 1a approach can be cross-checked using a Tier 1b method. In general, however, the simple methods tend to be based primarily on a Tier 1a approach (emission-factor approach) with the default emission factor being up to 100 percent for prompt release applications.

For simpler Tier 1 approaches, the chemical sales data at the application level is usually sufficient. However, separating out individual components of blends can still represent a considerable challenge. Irrespective of the Tier 1 methodology chosen, countries will need to report emissions of individual HFCs and PFCs. Information on the practical use of the various commercial types of HFC/PFC refrigerants, blowing agents, solvents, etc. will therefore be required. Many of these products are mixtures of two or more HFCs and/or PFCs, and the composition of fluids for similar purposes may vary according to individual formulas developed by different chemical companies.

Tier 1a – Emission-factor approach at the application level

Tier 1a relies on the availability of basic activity data at the application level, rather than at the level of equipment or product type (sub-application). This activity data may consist of annual chemical consumption data and, for applications exhibiting delayed emissions, banks derived therefrom. Once activity data have been established at the application level, composite emission factors (see Section 7.1.2.3) are then also applied at the application level. These more aggregated emission factors (e.g., all rigid foams) can be a composite or weighted average of the emission factors developed for Tier 2a covering individual equipment or product types, or can be a validated approximation approach (e.g., Gamlen *et al.* 1986).

The calculation formula for Net Consumption within the Tier 1a method is as follows:

EQUATION 7.1

CALCULATION OF NET CONSUMPTION OF A CHEMICAL IN A SPECIFIC APPLICATION

$$Net\ Consumption = Production + Imports - Exports - Destruction$$

Net Consumption values for each HFC or PFC are then used to calculate annual emissions for applications exhibiting prompt emissions as follows:

EQUATION 7.2A

CALCULATION OF EMISSIONS OF A CHEMICAL FROM A SPECIFIC APPLICATION

$$Annual\ Emissions = Net\ Consumption \bullet Composite\ EF$$

Where:

Net Consumption = net consumption for the application

Composite EF = composite emission factor for the application

Note that, as discussed in the Choice of Activity Data section, inventory compilers may have access to chemical consumption data at the aggregate level rather than by application. In this case, it will be necessary as an early step to determine the share of total consumption represented by each application.

In equation 7.1, *Production* refers to production of new chemical. Reprocessing of recovered fluid should not be included in consumption estimates. *Imports* and *Exports* include bulk chemicals but, for a Tier 1 method is unlikely to contain the quantity of chemical contained in products, such as refrigerators, air-conditioners, packaging materials, insulating foams, fire extinguishers etc. unless regional allocation system or other method of approximation has been used. The term *composite emission factor* refers to an emissions rate that summarises the emissions rates of different types of equipment, product or, more generally, sub-applications within an ODS application area. Composite emission factors should account for assembly, operation and, where relevant in the time-series, disposal emissions.

Although destruction of virgin HFCs and PFCs is not currently practised widely, and may be technically difficult in some cases (UNEP TEAP Task Force on Destruction Technologies (UNEP-TEAP, 2002)), it should be included as a potential option to reduce consumption. It should be noted that destruction of virgin chemicals, as considered here, is distinct from the destruction of HFCs and PFCs in the end-of-life phase, which is strictly an emission reduction measure. By-product emissions during HFC/PFC production and fugitive emissions related to production and distribution have to be calculated separately.

Even in simple Tier 1a methods, it is usually necessary to account for the potential development of banks, where these can occur. Banks are the amounts of chemical that have accumulated throughout the lifecycle, either in supply chains, products, equipment or even waste streams but which, as of the end of the most recent year, has not been emitted. At the application level, banks can be estimated using relatively straight-forward algorithms and assumptions provided that the historic Net Consumption is known for each year following the introduction of the substance or, where this period exceeds the average lifetime of the product or equipment, over that average lifetime. Relevant application level emission factors are then applied to the banks to deal with emissions during the lifetime of the products or equipment. This same process is carried out for Tier 2a methods but, in that case, at the sub-application level. More general information on banks is contained in Section 7.1.2.1.

In cases where banks occur, Equation 7.2a is then modified to the following:

EQUATION 7.2B

CALCULATION OF EMISSIONS OF A CHEMICAL FROM AN APPLICATION WITH BANKS

$$\begin{aligned} Annual\ Emissions = {} & Net\ Consumption \bullet Composite\ EF_{FY} \\ & + Total\ Banked\ Chemical \bullet Composite\ EF_{B} \end{aligned}$$

Where:

Net Consumption = net consumption for the application

Composite EF_{FY} = composite emission factor for the application for first year

Total Banked Chemical = bank of the chemical for the application

Composite EF_{B} = composite emission factor for the application for bank

Composite emission factors are determined by taking an average of the applicable sub-application emission factors, weighted according to the activity in each sub-application. Sub-application emission factors can be country-specific where known or default. In practice, if sub-application data are known, inventory compilers would opt for a Tier 2 (disaggregated approach). If only application level data are known, representative composite emission factors from other studies or default composite emission factors provided in this chapter can be used.

Tier 1b – Mass-balance approach at the application level

The mass balance approach also estimates emissions from assembly, operation, and disposal, but does not rely on emission factors. Instead, the method uses measured consumption (i.e., sales) of each chemical in the country or facility being considered. It is generally limited to ODS Substitutes contained in pressurised systems. The general equation is as follows[5]:

EQUATION 7.3
GENERAL MASS BALANCE EQUATION FOR TIER 1B

$$\begin{aligned} Emissions = {} & Annual\ Sales\ of\ New\ Chemical - (Total\ Charge\ of\ New\ Equipment \\ & - Original\ Total\ Charge\ of\ Retiring\ Equipment) \end{aligned}$$

Industry needs to purchase new chemical from manufacturers in order to replace leakage (i.e., emissions) from the current equipment stock, or the equipment will not function properly. If the equipment stock did not change from year to year, then annual chemical consumption alone would provide a reasonable estimate of actual leakage or emissions. The total equipment stock, and the chemical charge it contains, however, does change from year to year. Some amount of new equipment containing a chemical charge is introduced each year, and some amount of old equipment that was charged originally is retired each year. If the total chemical charge contained in all equipment is increasing as a result of this annual turnover, then total annual chemical consumption will overestimate emissions (i.e., the charge contained in new equipment is greater than the original charge of the retired equipment). Conversely, if the total chemical charge in all equipment is decreasing, then total annual chemical consumption will underestimate emissions.

In order to make good use of data on annual sales of new chemical, it is therefore also necessary to estimate the total charge contained in new equipment, and the original charge contained in retiring equipment. The total charge of new equipment minus the original total charge of retiring equipment represents the net change in the charge of the equipment stock. (Using the mass balance approach, it is *not* necessary to know the total amount of each chemical in equipment stock in order to calculate emissions.) Where the net change is positive, some of the new chemical is being used to satisfy the increase in the total charge, and therefore cannot be said to replace emissions from the previous year.

Industry also requires new chemical to replace destroyed gas and for stockpiles. Additionally, not all equipment will be serviced annually. Terms can be added to the general equation to account for these factors but are not typically adopted within simple Tier 1b methods.

This approach is most directly applicable to the pressure equipment used in refrigeration and air conditioning, and fire protection applications because these are where chemical sales are most typically used to offset operational emissions. However, since the basic method is relatively simple to apply, it is more typical to extend the approach to the sub-application level (i.e., a Tier 2b method). Further elaboration and modification of this approach is provided in the description of each application. In practice, Tier 1b methods are most commonly used as a further cross-check to Tier 1a methods. Where basic Net Consumption data is lacking, regional and international databases and models have been developed that allocate regional chemical sales for different end uses (sub-applications) at a country level. These can therefore be used to source relevant data.

Tier 2 methods – applied at the sub-application level

There are two versions of the Tier 2 method, both of which result in emission calculations for each individual chemical and distinct types of products or equipment at the sub-application level or within a sub-application. The individual chemicals and products/equipment within the sub-application form the matrix referred to earlier in this section and their analysis is comparable with methods currently applied by the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) for CFCs, HCFCs and HFCs (McCulloch, Midgley and Ashford, 2001 and 2003; Ashford, Clodic, Kuijpers and McCulloch, 2004).

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[5] Boundary conditions: If there is no net change in the total equipment charge, then annual sales are equal to emissions. If the net change in the total equipment charge is equal to annual sales, then emissions are zero.

Both versions of the Tier 2 methodology follow two general steps:

a) Calculation or estimation of the time series of net consumption of each individual HFC and PFC chemical at a relatively detailed product and equipment level to establish the consumption basis for emission calculations. (e.g., refrigerators, other stationary refrigeration/AC equipment, appliance foams, insulated panels, pipe insulation, etc.)

b) Estimation of emissions using the activity data and resulting bank calculations derived from step (i), and either emission factors that reflect the unique emission characteristics related to various processes, products and equipment (Tier 2a) or, relevant new and retiring equipment information at the sub-application level to support a mass balance approach. (Tier 2b).

The difference between Tier 2a and Tier 2b is the same as that for Tier 1a and Tier 1b – namely Tier 2a methods use an emission-factor approach while Tier 2b methods follow a mass-balance approach. Both, however, need to be operated at a level of disaggregation appropriate to a Tier 2 method, typically at least at the sub-application level.

If the requisite data are available, a Tier 2 method is preferred for estimating emissions from ODS substitutes, particularly where the sub-applications within an overall application area are relatively heterogeneous. Some countries may already have the relevant information available to apply a Tier 2 methodology. Other countries might not have access to data for Tier 2 at present, but they are encouraged to establish routines to collect either country-specific or globally or regionally-derived activity data by chemical and sub-application within an application area (e.g., different types of refrigeration and air conditioning sub-applications). Tier 1, in contrast, requires data collection at a more aggregated application level (e.g., refrigeration and air conditioning in its totality).

As a first step in using the Tier 2 method, countries may wish to make first order approximation of the information needed for step (i). This will give direction to more focused data collection efforts in certain application areas or sub-categories. Table 7.3 gives the consumption distribution for all application areas in 2015 for the Article 5 (mainly developing countries) and Non-Article 5 Parties (developed countries) to the Montreal Protocol. The distribution is based on estimated consumption of ODS-substitutes in metric tonnes (UNEP-TEAP 2016b).

Table 7.3a and 7.3b gives the consumption of ODS-substitutes for the application category Refrigeration and Air Conditioning in 2015 for Article 5 and Non-Article 5 Parties, by substance and sub-application.

Table 7.3c shows the share of total consumption used for manufacturing (filling of new equipment) and servicing (refilling of operating equipment).

Good practice guidance in this section deals with variations of the Tier 2 method. Tier 1 methods, covered previously, are generally seen as default methods where the application is not a *key category* and data availability is limited. (Exceptionally, for Fire Protection, Tier 1a method with country-specific activity data and emission factor will be used in the case it is identified as *key category*.) Each sub-section of Sections 7.2 to 7.7 discusses how to apply these methods to specific ODS applications, reviews existing data sources, and identifies gaps therein.

TABLE 7.3 (UPDATED)
DISTRIBUTION OF HFC USE BY APPLICATION AREA FOR 2015

Country	Refrigeration and Air conditioning	Aerosols	Foam blowing agents	Fire protection and others
Article 5 Parties[a]	88 %	6 %	3 %	3 %
Non-Article 5 Parties[a]	57 %	22 %	19 %	2 %

Source: UNEP-TEAP (2016b)

[a] See list of Article 5 and Non-Article 5 Parties to the Montreal protocol at the Unep Ozone Secreteriat web page

Table 7.3a (New)
HFC consumption for Refrigeration and air conditioning in article 5 parties[a], percent of total by substance and sub-application area for 2015

	Total	HFC-134a	R-410A	R-407C	R-404A	R-507
Total	100	27	39	20	7	7
Stationary Air Conditioning	60	1	39	20	-	-
Mobile Air Conditioning	19	19	-	-	-	-
Commercial Refrigeration[b)]	13	2	-	-	6	6
Domestic Refrigeration	5	5	-	-	-	-
Industrial Refrigeration[b)]	2	<1	-	-	1	1
Transport Refrigeration[b)]	1	<1	-	-	<1	<1

Source: UNEP (2017)

[a] See list of Article 5 Parties to the Montreal protocol at the Unep Ozone Secreteriat web page

[b] Due to rounding, sums of individual items may not equal the totals

Table 7.3b (New)
HFC consumption for Refrigeration and air conditioning in non-article 5 parties[a], percent of total by substance and sub-application area for 2015

	Total	HFC-134a	R-410A	R-407C	R-404A
Total	100	39	39	13	9
Stationary Air Conditioning	54	2	39	13	-
Mobile Air Conditioning	34	34	-	-	-
Commercial Refrigeration	11	2	-	-	8
Industrial Refrigeration			-	-	1
Transport Refrigeration			-	-	
Domestic Refrigeration	1	1	-	-	-

Source: UNEP-TEAP (2016b)

[a] See list of Article 5 Parties to the Montreal protocol at the Unep Ozone Secreteriat web page

Table 7.3c (New)
HFC consumption for Refrigeration and air conditioning, Per cent of Total by manufacturing and servicing for 2015

	Manufacturing	Servicing
Article 5 Parties[a]	68	32
Non-Article 5 Parties[a]	53	47

Source: UNEP-TEAP (2016b)

[a] See list of Article 5 and Non-Article 5 Parties to the Montreal protocol at the Unep Ozone Secreteriat web page

Tier 2a – Emission-factor approach

The country-specific data required for a Tier 2a approach are derived from the number of products and end-uses relevant to each sub-application in which ODS substitutes are contained and from which ODS substitutes are ultimately emitted. This approach seeks information on the number of equipment units or products that use these chemicals, average chemical charges, average service life, emission rates, recycling, disposal, and other pertinent parameters. This information is generally collected at the level of distinct groups of products or equipment (e.g., for rigid foams: integral skin, continuous panel, discontinuous panel, appliance, injected foam products and others). Annual emissions are then estimated as a function of these parameters through the life of the units or products by the application of emission factors that are relevant to the lifecycle phases. Since equipment and other products vary significantly in the amount of chemical used, service life, and emission rates, the characterisation of this equipment can be a resource intensive task. The longer-lived the end-use equipment or product, and the more diverse the types of equipment or product within a particular sub-application, the more complex the sourced data approach has to be in order to account for emissions. However, the approach can provide an accurate estimate of emissions if the data called for by the following equation are available for all relevant types and vintages of equipment or product:

EQUATION 7.4

SUMMARY EMISSIONS EQUATION BASED ON PHASES OF THE LIFECYCLE

$$\begin{aligned} \textit{Total Emissions of Each PFC or HFC} &= \textit{Assembly/Manufacturing Emissions} \\ &+ \textit{Operation Emissions} \\ &+ \textit{Disposal Emissions} \end{aligned}$$

Manufacturing or Assembly Emissions occur as fugitives when new equipment is filled for the first time with a chemical or when a product is manufactured. *Operational Emissions* from equipment and products occur as leaks or by diffusion during the use phase of the product or equipment (including servicing). In some cases, there can even be intentional releases during operation. Finally, *Disposal Emissions* can occur when the equipment or product reaches its end-of-life and is decommissioned and disposed of. In this case, the remaining HFC/PFC in the product or equipment may escape to the atmosphere, be recycled, or possibly destroyed.

As with the Tier 1a method, there is a need to make provision for the development of banks in some applications. This can lead to complex multiple calculations at the sub-application level, since the dynamics of banks may vary considerably. However, because the individual algorithms rely on a simple sequential calculation of non-emitted consumption (i.e., consumption – emissions for each successive year), excellent emission assessments can result from a well-constructed and well-maintained national model.

The need to update equipment and product inventories on an annual basis can be a major implementation challenge for inventory compilers with limited resources. This challenge is made somewhat easier because it may not be necessary to collect annual chemical consumption if a comprehensive set of other market parameters is available (e.g., number of domestic refrigerators produced, etc.) In some countries or regions, trade associations can be a significant source of such data. Otherwise, specific market research may be necessary. Where such market parameters are the primary source of activity data, the potential magnitude of errors that can be introduced by small discrepancies at unit level makes it *good practice* to carry out a chemical consumption data cross-check to act as a means of providing quality assurance. The relevant QA/QC sections of this chapter give guidance on how to conduct such cross-checks for each relevant application.

In order to limit the burden of data management for both annual consumption data and the status of banks, it is possible to access international and regional databases of such information to gain the necessary inputs of globally or regionally validated data to maintain a national model. These databases can also help to overcome any confidentiality barriers that may exist in collecting and/or publishing data at a national level, particularly where the number of suppliers is low. More information on the use of such databases is contained in Section 7.1.2.4 and Box 7.1.

Even where comprehensive country-specific activity data exists at a country level, it is *good practice* to benchmark outputs against assessments made from databases of globally or regionally derived data. This need not be done on an annual basis but could reasonably be conducted every 2-3 years. Significant discrepancies can then be analysed and suitable actions taken to reconcile differences.

Tier 2b – Mass-balance approach

Tier 2 mass-balance approaches are similar to those described for Tier 1b, except that the process is applied at the sub-application level. This is a particularly valuable approach for the refrigeration sector where there are a significant number of relatively heterogeneous sub-applications. As is also the case for Tier 1 methods, it is not uncommon to see mass-balance approaches used in combination with emission-factor approaches to ensure that the outputs achieved are as robust as possible. Such approaches can realistically be described as hybrid Tier 2a/b methods and they will be identified as such, where they occur in the relevant application-specific sections that follow.

Since mass-balance approaches also require activity data at the sub-application level, it may be more resource-efficient to use global or regional databases to obtain appropriate globally or regionally validated data. The same criteria for selection as set out for Tier 2a methods also apply for Tier 2b methods. Accordingly, equal care should be taken in selecting validated datasets.

7.1.2.3 CHOICE OF EMISSION FACTORS

No refinement.

7.1.2.4 CHOICE OF ACTIVITY DATA

No refinement.

7.1.2.5 COMPLETENESS

No refinement.

7.1.2.6 DEVELOPING A CONSISTENT TIME SERIES

No refinement.

7.1.3 Uncertainty assessment

No refinement.

7.1.4 Quality Assurance/Quality Control (QA/QC), Reporting and Documentation for all ODS substitutes applications

No refinement.

7.2 SOLVENTS (NON-AEROSOL)

No refinement.

7.3 AEROSOLS (PROPELLANTS AND SOLVENTS)

No Refinement.

7.4 FOAM BLOWING AGENTS

No refinement.

7.5 REFRIGERATION AND AIR CONDITIONING

7.5.1 Chemicals covered in this application area

Refrigeration and air-conditioning (RAC) systems may be classified in up to six sub-application domains or categories (UNEP-RTOC, 2003), although fewer sub-applications may be used in some countries. These categories correspond to sub-applications that may differ by location and purpose, and are listed below:

a) Domestic (i.e., household) refrigeration,

b) Commercial refrigeration including different types of equipment, from vending machines to centralised refrigeration systems in supermarkets,

c) Industrial processes including chillers, cold storage, and industrial heat pumps used in the food, petrochemical and other industries,

d) Transport refrigeration including equipment and systems used in refrigerated trucks, containers, reefers, and wagons,

e) Stationary air conditioning including air-to-air systems, heat pumps, and chillers[6] for building and residential applications,

f) Mobile air-conditioning systems used in passenger cars, truck cabins, buses, and trains.[7]

For all these sub-applications, different HFCs are progressively replacing CFCs and HCFCs. For example, in developed and several developing countries, HFC-134a has replaced CFC-12 in domestic refrigeration, high-pressure chillers and mobile air conditioning systems, and blends of HFCs such as R-407C (HFC-32/HFC-125/HFC-134a) and R-410A (HFC-32/HFC-125) are replacing HCFC-22 mainly in stationary air conditioning. HFC blends R-404A (HFC-125/HFC-143a/HFC-134a) and R-507A (HFC-125/HFC-143a) have replaced R-502 (CFC-22/CFC-115) and HCFC-22 in commercial refrigeration. Other, non-HFC substances are also used to replace CFCs and HCFCs such as iso-butane (HC-600a) in domestic refrigeration or ammonia in industrial refrigeration.

A large number of blends containing HFCs and/or PFCs are being used in Refrigeration and Air Conditioning applications. Table 7.8 shows some of these blends. A more comprehensive list can be obtained at the UNEP Ozone Secretariat web site (https://ozone.unep.org/sites/default/files/Data-Reporting-Instructions-English.2019-03-20.pdf) or by contacting The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

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[6] Comfort air conditioning in large commercial buildings (including hotels, offices, hospitals, universities, etc.) is commonly provided by water chillers coupled with an air handling and distribution system.

[7] The sub-application of mobile air conditioning systems is likely to represent the largest share of HFC emissions within the Refrigeration and Air Conditioning application for many countries. See Section 7.5.2.4, Applying Tier 2 Methods – The Example Of Mobile Air Conditioning (MAC), for an example of how to calculate these emissions. The reader will see that limited information is needed to approximate these emissions, and essentially becomes a simple multiplication of an average emission factor and the number of cars with HFC air conditioning, and possibly adding emissions relating to container management, charging and end-of-life.

TABLE 7.8
BLENDS (MANY CONTAINING HFCS AND/OR PFCS)

Blend	Constituents	Composition (%)
R-400	CFC-12/CFC-114	Should be specified[1]
R-401A	HCFC-22/HFC-152a/HCFC-124	(53.0/13.0/34.0)
R-401B	HCFC-22/HFC-152a/HCFC-124	(61.0/11.0/28.0)
R-401C	HCFC-22/HFC-152a/HCFC-124	(33.0/15.0/52.0)
R-402A	HFC-125/HC-290/HCFC-22	(60.0/2.0/38.0)
R-402B	HFC-125/HC-290/HCFC-22	(38.0/2.0/60.0)
R-403A	HC-290/HCFC-22/PFC-218	(5.0/75.0/20.0)
R-403B	HC-290/HCFC-22/PFC-218	(5.0/56.0/39.0)
R-404A	HFC-125/HFC-143a/HFC-134a	(44.0/52.0/4.0)
R-405A	HCFC-22/ HFC-152a/ HCFC-142b/PFC-318	(45.0/7.0/5.5/42.5)
R-406A	HCFC-22/HC-600a/HCFC-142b	(55.0/14.0/41.0)
R-407A	HFC-32/HFC-125/HFC-134a	(20.0/40.0/40.0)
R-407B	HFC-32/HFC-125/HFC-134a	(10.0/70.0/20.0)
R-407C	HFC-32/HFC-125/HFC-134a	(23.0/25.0/52.0)
R-407D	HFC-32/HFC-125/HFC-134a	(15.0/15.0/70.0)
R-407E	HFC-32/HFC-125/HFC-134a	(25.0/15.0/60.0)
R-408A	HFC-125/HFC-143a/HCFC-22	(7.0/46.0/47.0)
R-409A	HCFC-22/HCFC-124/HCFC-142b	(60.0/25.0/15.0)
R-409B	HCFC-22/HCFC-124/HCFC-142b	(65.0/25.0/10.0)
R-410A	HFC-32/HFC-125	(50.0/50.0)
R-410B	HFC-32/HFC-125	(45.0/55.0)
R-411A	HC-1270/HCFC-22/HFC-152a	(1.5/87.5/11.0)
R-411B	HC-1270/HCFC-22/HFC-152a	(3.0/94.0/3.0)
R-411C	HC-1270/HCFC-22/HFC-152a	(3.0/95.5/1.5)
R-412A	HCFC-22/PFC-218/HCFC-142b	(70.0/5.0/25.0)
R-413A	PFC-218/HFC-134a/HC-600a	(9.0/88.0/3.0)
R-414A	HCFC-22/HCFC-124/HC-600a/HCFC-142b	(51.0/28.5/4.0/16.5)
R-414B	HCFC-22/HCFC-124/HC-600a/HCFC-142b	(50.0/39.0/1.5/9.5)
R-415A	HCFC-22/HFC-152a	(82.0/18.0)
R-415B	HCFC-22/HFC-152a	(25.0/75.0)
R-416A	HFC-134a/HCFC-124/HC-600	(59.0/39.5/1.5)
R-417A	HFC-125/HFC-134a/HC-600	(46.6/50.0/3.4)
R-418A	HC-290/HCFC-22/HFC-152a	(1.5/96.0/2.5)
R-419A	HFC-125/HFC-134a/HE-E170	(77.0/19.0/4.0)
R-420A	HFC-134a/HCFC-142b	(88.0/12.0)
R-421A	HFC-125/HFC-134a	(58.0/42.0)

TABLE 7.8 (CONTINUED)
BLENDS (MANY CONTAINING HFCS AND/OR PFCS)

Blend	Constituents	Composition (%)
R-422A	HFC-125/HFC-134a/HC-600a	(85.1/11.5/3.4)
R-422B	HFC-125/HFC-134a/HC-600a	(55.0/42.0/3.0)
R-422C	HFC-125/HFC-134a/HC-600a	(82.0/15.0/3.0)
R-500	CFC-12/HFC-152a	(73.8/26.2)
R-501	HCFC-22/CFC-12	(75.0/25.0)
R-502	HCFC-22/CFC-115	(48.8/51.2)
R-503	HFC-23/CFC-13	(40.1/59.9)
R-504	HFC-32/CFC-115	(48.2/51.8)
R-505	CFC-12/HCFC-31	(78.0/22.0)
R-506	CFC-31/CFC-114	(55.1/44.9)
R-507A	HFC-125/HFC-143a	(50.0/50.0)
R-508A	HFC-23/PFC-116	(39.0/61.0)
R-508B	HFC-23/PFC-116	(46.0/54.0)
R-509A	HCFC-22/PFC-218	(44.0/56.0)

[1] R-400 can have various proportions of CFC-12 and CFC-114. The exact composition needs to be specified, e.g., R-400 (60/40).

7.5.2 Methodological issues

7.5.2.1 CHOICE OF METHOD

As discussed in the introductory section to this chapter, both Tier 1 and Tier 2 result in estimates of *actual* emissions rather than estimates of *potential* emissions. Actual estimates, which account for the lag between consumption and emissions, are particularly important for both the refrigeration and air conditioning sector because of the potentially long retention of refrigerants in products and equipment utilised in these applications.

The options available to the refrigeration and air conditioning application are shown in the decision tree shown in Figure 7.6.

TIER 1

Tier 1 a/b

It is expected that the refrigeration and air conditioning will be a *key category* for many countries. The implication of this conclusion from Table 7.2 and the decision tree in Figure 7.6 is that either country-specific or globally or regionally derived activity data will be required at the sub-application (disaggregated) level in order to complete the reporting task. However, in the rare instances that the refrigeration and air conditioning application is much less significant, there should be available a suitable Tier 1 method for aggregated data.

From experience of studying the dynamics of refrigerant consumption and banks in several countries (UNEP-RTOC, 2003; Ashford, Clodic, Kuijpers and McCulloch, 2004; and supporting materials), it is possible to derive assumptions that allow for the assessment of the use of refrigerant that may help in assessing sales of a given refrigerant at a country level. Such a hybrid Tier 1a/b approach may use the following assumptions:

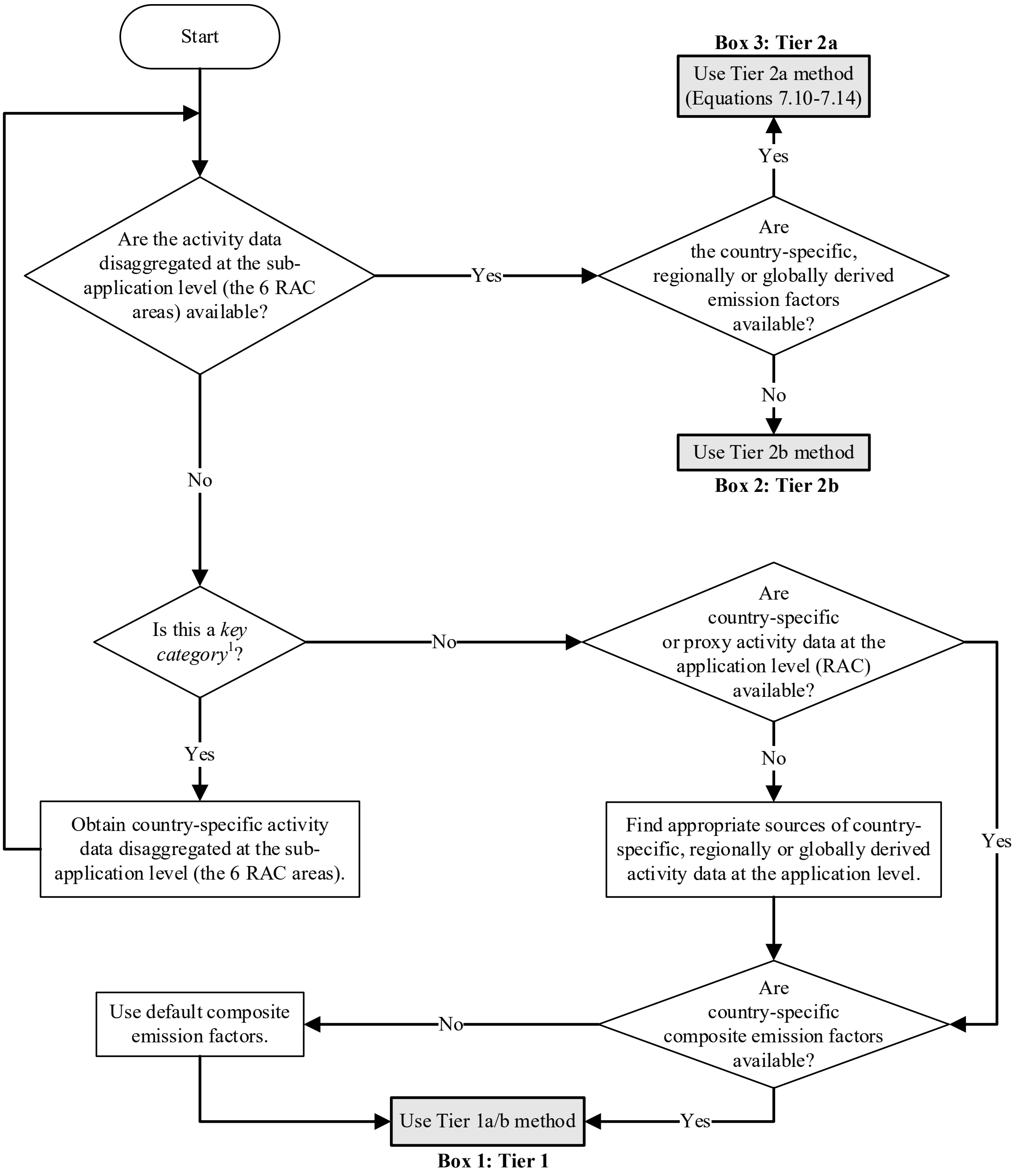
1. Servicing of equipment containing the refrigerant does not commence until 3 years after the equipment is installed.
2. Emissions from banked refrigerants average 15 percent annually across the whole RAC application area. This assumption is estimated to be a weighed average across all sub-applications, for which default emission factors are shown in Table 7.9.
3. In a mature market two thirds of the sales of a refrigerant are used for servicing and one third is used to charge new equipment. A mature market is one in which ODS substitute-employing refrigeration equipment is in wide use, and there are relationships between suppliers and users to purchase and service equipment.
4. The average equipment lifetime is 15 years. This assumption is also estimated to be a weighed average across all sub-applications.
5. The complete transition to a new refrigerant technology will take place over a 10 year period. From experiences to date, this assumption is believed to be valid for a single chemical in a single country.

With these assumptions in place, it is possible to derive emissions, if the following data can be provided:

- Sales of a specific refrigerant in the year to be reported
- Year of introduction of the refrigerant
- Growth rate in sales of new equipment (usually assumed linear across the period of assessment)
- Assumed percentage of new equipment exported
- Assumed percentage of new equipment imported

The Tier 1a/b method then back-calculates the development of banks of a refrigerant from the current reporting year to the year of its introduction. In mapping this period, the method also models the transition from sales to new equipment (100 percent initially) to the mature market position assumed based on experience to be 33 percent to new equipment and 67 percent to servicing requirements. It is assumed that the transition to new refrigerant technology is reflected identically in any imported equipment.

Figure 7.6 Decision tree for actual emissions from the refrigeration and air conditioning (RAC) application



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.

The following spreadsheet example indicates how the Tier 1a/b method would estimate a seven-year time series of emissions of the selected refrigerant, following its initial introduction in 1998, with the knowledge that there were sales of 1 000 tonnes in 2005. The spreadsheet contained in the *2006 IPCC Guidelines* CDROM mirrors this calculation, and globally or regionally derived datasets[8] at both application and consolidated sub-application levels should be available at a country level to assist in completion of this spreadsheet.

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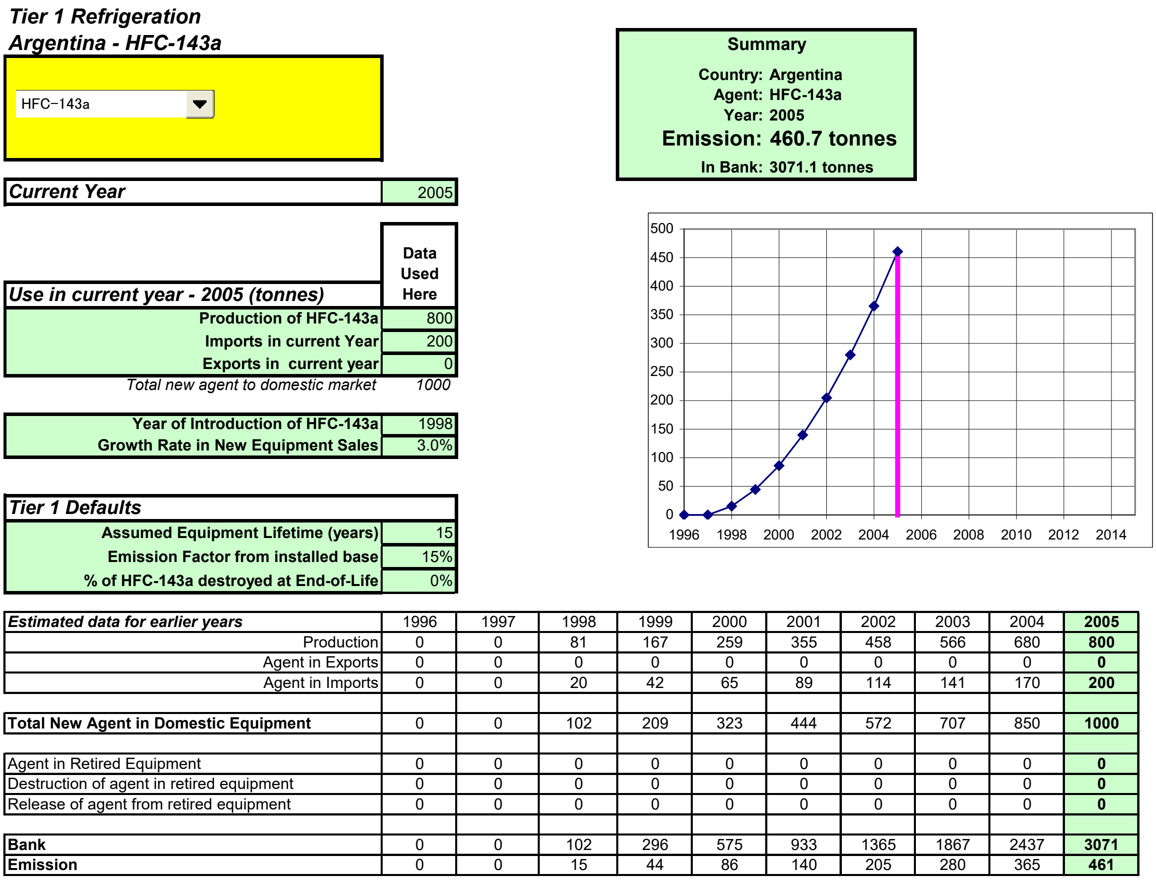
[8] As noted in Box 7.1, inclusion in the IPCC Emission Factor Database (EFDB) will indicate general adherence to due process, but it is *good practice* for countries to ensure that all data taken from the EFDB are appropriate for their national circumstances.

Figure 7.7 Example of spreadsheet calculation for Tier 1a/b assessments



Tier 1 Refrigeration
Argentina - HFC-143a

HFC-143a

Summary
Country: Argentina
Agent: HFC-143a
Year: 2005
Emission: 460.7 tonnes
In Bank: 3071.1 tonnes

Current Year	2005

Use in current year - 2005 (tonnes)	**Data Used Here**
Production of HFC-143a	800
Imports in current Year	200
Exports in current year	0
Total new agent to domestic market	*1000*

Year of Introduction of HFC-143a	1998
Growth Rate in New Equipment Sales	3.0%

Tier 1 Defaults	
Assumed Equipment Lifetime (years)	15
Emission Factor from installed base	15%
% of HFC-143a destroyed at End-of-Life	0%

Estimated data for earlier years	1996	1997	1998	1999	2000	2001	2002	2003	2004	**2005**
Production	0	0	81	167	259	355	458	566	680	**800**
Agent in Exports	0	0	0	0	0	0	0	0	0	**0**
Agent in Imports	0	0	20	42	65	89	114	141	170	**200**
Total New Agent in Domestic Equipment	0	0	102	209	323	444	572	707	850	**1000**
Agent in Retired Equipment	0	0	0	0	0	0	0	0	0	**0**
Destruction of agent in retired equipment	0	0	0	0	0	0	0	0	0	**0**
Release of agent from retired equipment	0	0	0	0	0	0	0	0	0	**0**
Bank	0	0	102	296	575	933	1365	1867	2437	**3071**
Emission	0	0	15	44	86	140	205	280	365	**461**

In this hypothetical example, the production of a specific refrigerant are 800 tonnes with an additional 200 tonnes in imported equipment, in 2005 making a total consumption of 1 000 tonnes. Based on this consumption figure and knowledge of the year of introduction of the refrigerant, it can be seen that the Tier 1a/b method predicts emissions of 461 tonnes based on the development of banks over the previous seven years. The bank in 2005 is estimated at 3 071 tonnes.

It should be noted that, while such methods allow for the estimation of emissions when data are difficult to obtain, it is still necessary to have an accurate assessment of country-specific or globally or regionally derived net consumption activity data. When the content of Table 7.8 is considered (particularly when some of these blends may be being imported in equipment) it is clear that there needs to be considerable knowledge of technology selection in the market. Refrigerant suppliers should be able to assist inventory compilers in this area, but the burden of developing high quality activity datasets may lead inventory compilers to the conclusion that Tier 2 options provide more value with little extra work. Indeed, where globally or regionally validated data activity is sought, this will normally be a reconstitution of disaggregated data originally at the sub-application level, so it might be most logical to take full advantage of that versatility and pursue a Tier 2 approach from the outset.

TIER 2

Overview

The Tier 2a methodology:

a) Takes into account the phase out or the phase down of CFCs and HCFCs depending on the Montreal Protocol schedule and possible national or regional regulations, in order to establish the refrigerant choice for all applications;

b) Defines the typical refrigerant charge and the equipment lifetime per sub-application;

c) Defines the emission factors for refrigerant charge, during operation, at servicing and at end-of-life.

Calculation of emissions throughout the equipment lifetime requires deriving the total stock of equipment independent of their vintage. In doing so the refrigerant bank is established per sub-application.

In order to achieve consistency it is suggested to derive the annual market of refrigerants from the refrigerant quantities charged in the brand new equipment and from the refrigerant quantities used for servicing of the total stock of equipment.

The Tier 2b mass-balance approach relies on a knowledge of the annual sales of refrigerant, refrigerant destroyed and any changes in equipment stock that occur (i.e., new equipment sales and equipment decommissioned) on a sub-application basis. It does not require an absolute knowledge of equipment stocks or emission factors relating to each refrigeration and air conditioning sub-application.

Examples of how the Tier 2 methodology may be applied are given in the remainder of this section.

Tier 2b - Mass-balance approach

The mass-balance approach is particularly applicable to the Refrigeration and Air Conditioning application because of the significant servicing component required to maintain equipment. The general approach to Tier 2b is introduced in Chapter 1 of Volume 3.

For the mass-balance approach, the four emission stages (charging, operation servicing and end-of-life) identified above are addressed in the following simplified equation:

EQUATION 7.9
DETERMINATION OF REFRIGERANT EMISSIONS BY MASS BALANCE

$$\begin{aligned} Emissions &= Annual\ Sales\ of\ \ New\ Refrigerant - Total\ Charge\ of\ \ New\ Equipment \\ &\quad + Original\ Total\ Charge\ of\ \ Retiring\ Equipment - Amount\ of\ \ Intentional\ Destruction \end{aligned}$$

Annual Sales of New Refrigerant is the amount of a chemical introduced into the refrigeration sector in a particular country in a given year. It includes all chemical used to fill or refill equipment, whether the chemical is charged into equipment at the factory, charged into equipment after installation, or used to recharge equipment at servicing. It does not include recycled or reclaimed chemical.

Total Charge of New Equipment is the sum of the full charges of all the new equipment that is sold in the country in a given year. It includes both the chemical required to fill equipment in the factory and the chemical required to fill the equipment after installation. It does not include charging emissions or chemical used to recharge equipment at servicing.

Original Total Charge of Retiring Equipment is the sum of the full charges of all the retiring equipment decommissioned in a country in a given year. It assumes that the equipment will have been serviced right up to its decommissioning and will therefore contain its original charge.

Amount of Intentional Destruction is that quantity of the chemical duly destroyed by a recognised destruction technology.

In each country there is a stock of existing refrigeration equipment that contains an existing stock of refrigerant chemical (*bank*). Therefore, annual sales of new chemical refrigerant must be used for one of three purposes:

- To increase the size of the existing chemical stock (bank) in use (including retrofitting equipment from a previous chemical to the given chemical);
- To replace that fraction of last year's stock of chemical that was emitted to the atmosphere (through, for example, leaks or servicing losses);
- To provide supply-chain priming or stockpiles.

Since the third item in this list is rarely required in a steady-state market, it is not included in Equation 7.9. Terms to account for stockpiling and retrofitting could be added to Equation 7.9 if such situations exist.

The difference between the total quantity of gas sold and the quantity of that gas used to increase the size of the chemical stock equals the amount of chemical emitted to the atmosphere. The increase in the size of the chemical stock is equal to the difference between the total charges of the new and retiring equipment.

By using data on current and historical sales of gas, rather than emission factors referenced from literature, the equation reflects assembly, operation, and disposal emissions at the time and place where they occur. Default emission factors may not be accurate because emissions rates may vary considerably from country to country and even within a single country.

As discussed in Chapter 1, Section 1.5 of Volume 3, one drawback of the mass-balance approach is that it can underestimate emissions when equipment stocks are growing, because there is a lag between the time the emissions occur and the time they are detected (through equipment servicing). This underestimate will be relatively large in countries where HFCs have been used in equipment for less than ten years, because much of the equipment will have leaked without ever being serviced. Thus, countries where HFCs have been used for less than ten years are encouraged to estimate emissions using alternative approaches. In general, the longer HFCs are used in a country, the smaller the underestimate associated with the mass-balance approach. Once equipment containing HFCs begins to retire, the underestimate declines to a low level.

Equation 7.9 can be applied either to individual types of equipment (sub-applications), or more generally to all air conditioning and refrigeration equipment in a country (i.e., Tier 1b), depending on the level of disaggregation of available data. If disaggregated data are available, emissions estimates developed for each type of equipment and chemical are summed to determine total emissions for the application.

Tier 2a – Emission-factor approach

In a Tier 2a calculation, refrigerant emissions at a year **t** from each of the six[9] sub-applications of refrigeration and air conditioning systems are calculated separately. These emissions result from:

- $E_{containers,t}$ = emissions related to the management of refrigerant containers
- $E_{charge,t}$ = emissions related to the refrigerant charge: connection and disconnection of the refrigerant container and the new equipment to be charged
- $E_{lifetime,t}$ = annual emissions from the banks of refrigerants associated with the six sub-applications during operation (fugitive emissions and ruptures) and servicing
- $E_{end\text{-}of\text{-}life,t}$ = emissions at system disposal

All these quantities are expressed in kilograms and have to be calculated for each type of HFC used in the six different sub-applications.

EQUATION 7.10
SUMMARY OF SOURCES OF EMISSIONS

$$E_{total,t} = E_{containers,t} + E_{Charge,t} + E_{lifetime,t} + E_{end-of-life,t}$$

Methods for estimating average emission rates for the above-mentioned sectors are outlined below and need to be calculated on a refrigerant by refrigerant basis for all equipment regardless of their vintage. If information on container and charging emissions is not available, inventory compilers can estimate these losses as a percent of the bank and revise the lifetime (operation plus servicing) emission factor in Equation 7.13 below to account for such losses.

Refrigerant management of containers

The emissions related to the refrigerant container management comprises all the emissions related to the refrigerant transfers from bulk containers (typically 40 tonnes) down to small capacities where the mass varies from 0.5 kg (disposable cans) to 1 tonne (containers) and also from the remaining quantities - the so-called refrigerant *heels* (vapour and /or liquid) - left in the various containers, which are recovered or emitted.

EQUATION 7.11
SOURCES OF EMISSIONS FROM MANAGEMENT OF CONTAINERS

$$E_{containers,\,t} = RM_t \bullet \frac{c}{100}$$

Where:

$E_{containers,\,t}$ = emissions from all HFC containers in year t, kg

RM_t = HFC market for new equipment and servicing of all refrigeration application in year t, kg

c = emission factor of HFC container management of the current refrigerant market, percent

The emissions related to the complete refrigerant management of containers are estimated between 2 and 10 percent of the refrigerant market.

Refrigerant charge emissions of new equipment

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[9] More than six sub-applications can be used, depending on the level of disaggregated data available.

The emissions of refrigerant due to the charging process of new equipment are related to the process of connecting and disconnecting the refrigerant container to and from the equipment when it is initially charged.

EQUATION 7.12
SOURCES OF EMISSIONS WHEN CHARGING NEW EQUIPMENT

$$E_{charge,t} = M_t \bullet \frac{k}{100}$$

Where:

$E_{charge,t}$ = emissions during system manufacture/assembly in year t, kg

M_t = amount of HFC charged into new equipment in year t (per sub-application), kg

k = emission factor of assembly losses of the HFC charged into new equipment (per sub-application), percent

Note: the emissions related to the process of connecting and disconnecting during servicing are covered in Equation 7.13.

The amount charged (M_t) should include all systems which are charged in the country, including those which are produced for export. Systems that are imported pre-charged should not be considered.

Typical range for the emission factor k varies from 0.1 to 3 percent. The emissions during the charging process are very different for factory assembled systems where the emissions are low (see Table 7.9) than for field-erected systems where emissions can be up to 2 percent.

Emissions during lifetime (operation and servicing)

Annual leakage from the refrigerant banks represent fugitive emissions, i.e., leaks from fittings, joints, shaft seals, etc. but also ruptures of pipes or heat exchangers leading to partial or full release of refrigerant to the atmosphere. Besides component failures, such as compressor burn-out, equipment is serviced mainly when the refrigerating capacity is too low due to loss of refrigerant from fugitive emissions. Depending on the application, servicing will be done for instance every year or every three years, or sometimes not at all during the entire lifetime such as in domestic refrigeration sub-applications. For some sub-applications, leaks have to be fixed during servicing and refrigerant recovery may be necessary, so the recovery efficiency has to be taken into account when estimating emission factors. In addition, knowing the annual refrigerant needs for servicing per sub-application allows the determination of the national refrigerant market by adding the refrigerant quantities charged in new equipment (see Paragraph Quality assurance/Quality control). The following calculation formula applies:

EQUATION 7.13
SOURCES OF EMISSIONS DURING EQUIPMENT LIFETIME

$$E_{lifetime,t} = B_t \bullet \frac{x}{100}$$

Where:

$E_{lifetime,t}$ = amount of HFC emitted during system operation in year t, kg

B_t = amount of HFC banked in existing systems in year t (per sub-application), kg

x = annual emission rate (i.e., emission factor) of HFC of each sub-application bank during operation, accounting for average annual leakage and average annual emissions during servicing, percent

In calculating the refrigerant bank (B_t) all systems in operation in the country (produced domestically and imported) have to be considered on a sub-application by sub-application basis.

Examples of typical leakage rates (x) for various types of equipment describing the respective refrigeration sub-applications are given in Table 7.9.

Emissions at end-of-life

The amount of refrigerant released from scrapped systems depends on the amount of refrigerant left at the time of disposal, and the portion recovered. From a technical point of view, the major part of the remaining fluid can be recovered, but recovery at end-of-life depends on regulations, financial incentives, and environmental consciousness.

The following calculation formula (Equation 7.14) is applicable to estimate emissions at system disposal:

EQUATION 7.14
EMISSIONS AT SYSTEM END-OF-LIFE

$$E_{end-of-life,\,t} = M_{t-d} \bullet \frac{p}{100} \bullet (1 - \frac{\eta_{rec,\,d}}{100})$$

Where:

$E_{end\text{-}of\text{-}life,\,t}$ = amount of HFC emitted at system disposal in year t, kg

M_{t-d} = amount of HFC initially charged into new systems installed in year (t-d), kg

p = residual charge of HFC in equipment being disposed of expressed in percentage of full charge, percent

$\eta_{rec,d}$ = recovery efficiency at disposal, which is the ratio of recovered HFC referred to the HFC contained in the system, percent

In estimating the amount of refrigerant initially charged into the systems (M_{t-d}), all systems charged in the country (for the domestic market) and systems imported pre-charged should be taken into account.

BOX 7.2A (NEW)
HOW TO BUILD A REFRIGERATION AND AIR-CONDITIONING (R/AC) EMISSION INVENTORY IN A FEW SIMPLE STEPS. TIER 1 AND TIER 2 EMISSION FACTOR APPROACHES

Learn about the use of HFCs in R/AC

Tip! The "Fact sheets on HFCs" provided at the UNEP Ozone Secretariat web site, particularly the overview of HFC market sectors, is a good starting point for learning about the use of these chemicals. (See http://conf.montreal-protocol.org/meeting/workshops/hfc_management-02/presession/English/Forms/AllItems.aspx)

TIER 1a/b

1. The IPCC Worksheet

A basic calculation tool in the form of MS Excel worksheet "Calculation Example for 2F1" can be downloaded at the IPCC web site (https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol3.html).

2. Activity Data

Collect the data required as inputs to the calculations:

- Consumption of specific HFCs or other ODS substitutes, at least in the year to be reported
- Year of introduction of the refrigerant
- Growth rate in sales of new equipment

Look for data in, for example, Refrigerant Management Plans (RMPs), HCFC Phase-out Management Plans (HPMPs) or data reported under the Montreal Protocol. To get an idea of the most important gas types and application areas, see Tables 7.3a-d.

3. Emission Factors

Identify and apply the appropriate emission factors. The IPCC Worksheet contains the default Tier 1 emission factor. Modify the default emission factor according to country-specific conditions if information on these conditions is available.

TIER 2a

Where refrigeration and air conditioning is a *key category*, a Tier 2 approach should be used to estimate emissions. Building a good quality Tier 2 inventory for refrigerants is demanding, so setting up a plan for gradual improvement over time is recommended.

1. Calculation tools

The spreadsheet "Calculation example for 2F1 (Tier 2)" of the *2019 Refinement* can be used. Most countries have however built their own models, which are adapted to national conditions and to the data they have available.

2. Activity data

For the Tier 2 approach HFC consumption needs to be collected or estimated for each of the six sub-applications listed in Section 7.5.1.

Box 7.2b and Box 7.2c gives information on what data needs to be collected.

Data sources are described in Box 7.3a.

3. Emission factors

Table 7.9 provides ranges of default factors for the sub-applications if country-specific factors are not available. Choose from the ranges according to country-specific conditions and document the reasons for the choices. In general, the emission factors in the low end of the ranges apply for developed countries or those that have a voluntary or mandatory system in place to limit emissions during equipment service, use and disposal. Further discussion on the choice of emission factors is found in section 7.5.2.2.

BOX 7.2B (NEW)
THE BASIC ELEMENTS OF AN EMISSION INVENTORY FOR R/AC

Emissions of HFCs from refrigeration and air conditioning (R/AC) equipment are closely related to the amounts and types of chemicals in the bank of a country. A "bank” is the amount of HFCs and other fluorinated ODS-substitutes contained in equipment in use. It is therefore important for the inventory compiler to keep track of the bank and the flows of chemicals into and out of the bank. The following equation summarizes how the bank changes over the year due to emissions and other flows. More details are given in the spreadsheet "Calculation example for 2F1 (Tier 2)".

Estimation of annual refrigerant bank

$$Bank_y = Bank_{y-1} + Addition_y - Removal_y$$

Where:

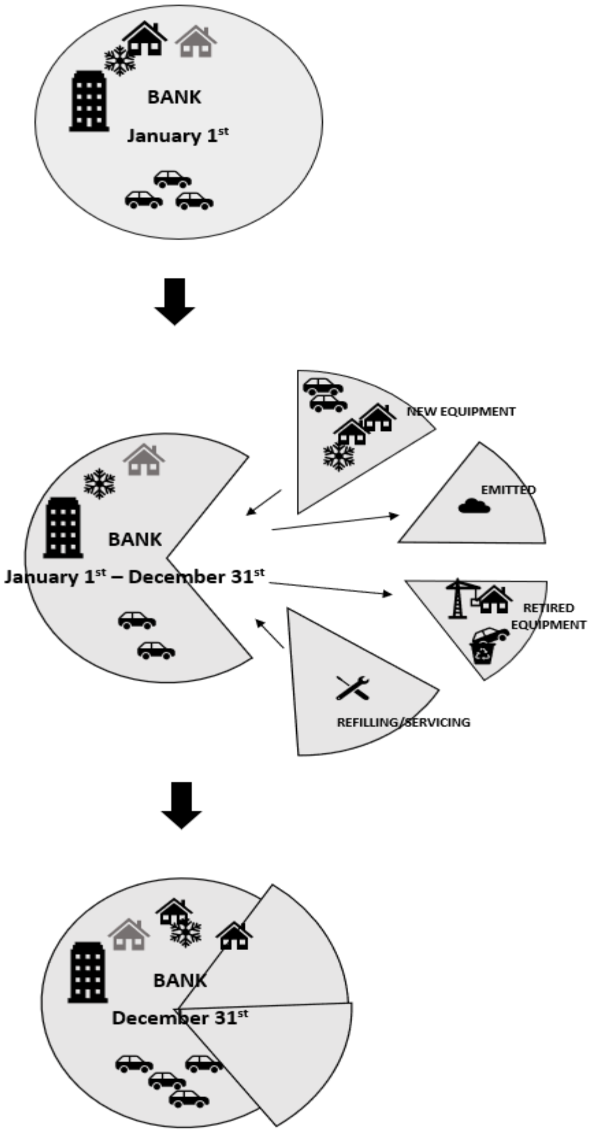
$Bank_y$ = Refrigerant bank on December 31st of year y, kg

$Bank_{y-1}$ = Refrigerant bank on December 31st of year y-1/January 1st of year y, kg

$Addition_y$ = Addition of new substances year y, kg

$Removal_y$ = Removal of substances exported, emitted or destroyed year y, kg

The figure below illustrates these relationships.



BOX 7.2B (NEW) (CONTINUED)
THE BASIC ELEMENTS OF AN EMISSION INVENTORY FOR R/AC

The Bank of HFCs

The starting point for the annual estimates is a *snapshot of the bank* of HFCs at the end of the previous year/beginning of the current year.

The bank is the amount of HFCs contained in equipment in use in a country, and a snapshot of the bank means that for each of the relevant sub-applications, you need to have an estimate of the types and amounts of HFCs it contains. For instance, you need to quantify the amount of HFC-134a in air conditioning units in cars, the amount of the blend R-410A in air conditioning used in buildings, R-404A used for refrigeration in supermarkets etc. See the list of chemicals and the equipment (sub-applications) in which they are normally contained in Table 7.1. Note that in a given year, equipment may contain substances other than HFCs. If this is the case, you need to estimate the share of HFCs in relation to the other substances (e.g. HCFC, NH3, etc.).

If you start the calculations at the beginning of the first year of HFCs entering the market in your country, there is no bank of chemicals and the bank at January 1st of year $y = 0$.

If you start making the inventory when HFCs are already in use in your country, you will have to spend time putting together information on what the bank currently looks like. See Box 7.2c on how to estimate the bank if the starting point of the inventory is not the first year of using HFC, i.e. when the bank at January 1st of year $y > 0$.

In the future, this kind of snapshot of the equipment population (bank) will be one of the outputs from the calculation model you run every year.

The flows of HFCs into and out of the bank

The bank will develop year by year depending on the amounts of HFC added to and removed from the bank. In order to keep track of the development of the bank, you need to collect data on or estimate these flows:

Flow of HFCs *into* the bank

HFC is mainly added to the bank through two processes: New equipment containing HFCs and the servicing (refilling) of equipment in use.

A common approach for quantifying the sum of the amount of HFC contained in new equipment added to the bank and the amount used for servicing, is to collect data on domestic sales of HFCs both **in bulk** and **in equipment**. Domestic sale is then the sum of **production** and **imports**, minus **exports.** If HFC is recovered in a country, this also needs to be taken into account, as the amount of HFCs recycled remains in the bank.

Only a few countries produce HFCs. This means that when collecting data for domestic sales of HFCs in bulk, most inventory compilers will solely need to quantify the imports. Ideally, you want to know the amount of each kind of HFC imported to your country, and what kind of sub-application it will be used in. You also need to collect data on (or estimate), the amount of HFC used for filling (production) of new equipment as opposed to the servicing of equipment already in use.

New equipment

HFC in new equipment is added to the bank when equipment is filled in the country or imported prefilled. HFC in exported equipment should not be added to the bank. See the spreadsheet "Calculation example for 2F1 (Tier 2)" for a detailed description on how to estimate the amount of HFCs entering the bank through new equipment and the emissions from this flow of chemicals.

BOX 7.2B (NEW) (CONTINUED)
THE BASIC ELEMENTS OF AN EMISSION INVENTORY FOR R/AC

For example, if your country does not produce HFC-134a or manufacture cars (i.e. fill air conditioning units of new cars with this chemical), the annual addition of HFC-134a through new cars will only consist of the amount contained in imported cars. If your country does manufacture cars, but does not produce HFCs, the annual addition in new equipment will consist of HFC-134a contained in imported cars *and* the amount of HFC-134a imported in bulk for filling (manufacturing) of new cars, minus the amount contained in exported cars.

See box 7.3a for tips on where to find data.

- **Refilling/servicing of equipment**

When existing equipment is being serviced and refilled with HFC, this will add to the bank. If data on servicing is difficult to obtain, a way of quantifying the amount used for this purpose is to assume it to be equal to the amount of chemicals emitted from operating equipment the previous year, taking into account that it should not exceed the amount of HFCs available in bulk. Another way to estimate the amount of HFCs used for servicing and refilling of equipment is to assume that it equals the estimated domestic sales minus the amount used for filling of new equipment.

Flow of HFCs *out* of the bank

HFC will mainly leave the bank through two processes: Emissions from the bank and through retired equipment.

- **Emissions during equipment lifetime**

Leakage of HFC from equipment in use, and hence emissions to the atmosphere, will remove chemicals from the bank. In the emission factor approach, this amount is estimated by applying an average emission factor per sub-application of equipment to the corresponding amount in the bank (equation 7.13). See Table 7.9 for default emission factors if national factors are not available. Note that the emission factors in Table 7.9 encompass annual leakage rates as well as emissions during service.

- **Retired equipment**

HFCs will also be removed from the bank when equipment is retired and scrapped or exported. Recycled HFC in the country will remain in the bank. The amount of HFCs in retired equipment is normally estimated based on average charge and the share of chemical remaining according to Table 7.9 and equation 7.14.

The fate of the HFCs contained in the retired equipment will also need to be quantified, often by a combination of data collection, assumptions and emission factors. It can be reclaimed and reused, destroyed or emitted. The used equipment containing HFC can also be exported to other countries. See "Calculation example for 2F1 (Tier 2)" for a more detailed description of the possible fates/flows and how to quantify them.

BOX 7.2C (NEW)
HOW TO BUILD THE BANK OF HFC

As described in Box 7.2B, it is essential to know the contents and structure of the bank of HFCs in order to estimate the emissions. In many cases this means that you need to quantify the bank from the year when HFCs were first used in a country up to the current year. There are two common ways of building the bank and the development back in time:

1. **Collecting historic data on domestic sales and flows of HFCs, starting at bank=0**

If data on domestic sales for all years since the HFCs were first introduced is available, this can be used to move forward from zero to the current bank by tracking the flow of chemicals into and out of the bank every year. This methodology is described in Box 7.2b.

2. **Counting the number of equipment currently in place and interpolate back to bank=0**

An alternative way of estimating the bank is to count the number of equipment units currently in place in a country and combine this with the average amount and type of HFCs contained in each type of equipment. This will provide an estimate of the current bank.

The historic development of the bank can be estimated by interpolation, i.e. filling in the holes in the time series between the year of introduction of HFC to the current situation (current amount in the bank). Refer to Volume 1, Chapter 5 for information on interpolation and other splicing techniques.

The following information on each of the relevant sub-applications need to be collected:

- The number of equipment units currently installed
- The average amount and type of HFC contained in each type of equipment
- The year of introduction, i.e. when HFC were first used in this kind of equipment in the country

Box 7.3a holds information on relevant data sources. For instance, the numbers of some kinds of equipment, like cars, might be available from national statistics or from a national register used for taxation. Industrial organizations often have statistics on mass-produced types of equipment, like numbers of household refrigerators, small air conditioning units, heat pumps and cars. If not, they might help you to estimate the sizes of markets, and hence consumption.

It is often challenging to get information on the number of large refrigeration and air conditioning systems. You might need to estimate this using information on the number of, for instance, large office buildings, hospitals, universities etc. in your country. Then you need to combine this with information on the typical number and types of air conditioning units per building. Again, industrial associations can often be helpful in getting this sort of information.

You need to collect information on the year each relevant kind of ODS-substitute was first used in each relevant type of equipment (sub-application) in your country (for instance, the year HFC-134a was first used in mobile air conditioning in your country). If this information is not available, you can make reasonable assumptions based on, for example, the ODS phase-out schedule in your country and/or substitution patterns in countries similar to yours.

Then, choose a method to fill in the years between year 0 and the current year. If you have no information on the development of the bank, a simple linear interpolation should be used. Otherwise, if some kind of information on the development is available, like the annual growth in sales of cars with air conditioning, this data can be used to model the bank year by year.

7.5.2.2 CHOICE OF EMISSION FACTORS

Tier 1a/b method

As explained within Section 7.5.2.1, Choice of Method, a composite emission factor is required to complete a Tier 1 method. Since the sub-applications within the refrigeration and air conditioning application are relatively heterogeneous, the validity of any single composite emission factor must be in doubt unless it takes into consideration the particular mix of sub-applications in the country. It is therefore *good practice* to develop composite emission factors on the basis of research within the country. The over-arching default emissions factor of 15 percent of the bank annually is used in the example of spreadsheet calculation, available at the IPCC web site: *https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol3.html*.

Tier 2a method

Good practice for choosing emission factors is to use country-specific data, based on information provided by equipment manufacturers, service providers, disposal companies, and independent studies. When national data are unavailable, inventory compilers should use the default emission factors shown in Table 7.9, Default Estimates for Charge, Lifetime and Emission Factors, which summarises best estimates of equipment charge, lifetime, emission factors during useful life, and parameters for end-of-life emissions. If data used to calculate the refrigerant bank cannot be broken down into the sub-applications as in Table 7.9, it is *good practice* to divide the bank by type of equipment using expert judgement, and calculate composite emission factors weighted according to that relative share, as described for Tier 1a/b.

Since the *2006 IPCC Guidelines* were published, only a few new studies on leakage rates from stationary refrigeration and AC and mobile AC for some developed countries or regions have been published. The studies covering stationary refrigeration and AC indicate that the default values in Table 7.9 are still valid and thus are retained. For mobile AC, Table 7.9 is updated to include separate information on charge and annual emission factor during operating lifetime for maritime, railways, busses and other mobile ACs, based on Schwarz and Rhiemeier (2007) and Gallagher et al (2014).

The values in Table 7.9 are provided as ranges rather than point estimates. Inventory compilers should choose from the range according to country-specific conditions and document the reasons for their choices. The lower end of the lifetime and emission factor ranges is expected to be applicable to developed countries and to countries that have a mandatory or voluntary system in place to limit emissions during equipment service and use. The upper end of each range is expected to be applicable to developing countries without systems for limiting emissions.

Studies of emission rates in Japan for 2008 (Nomura Research Institute, Ltd, 2012), California for 2008 (Gallagher, et. al., 2014) and Germany for 2009-2013 (Umweltbundesamt, 2015) confirmed that the average emission factors in these countries were close to the lower range for most sub-application categories within the application area of Stationary Refrigeration and Air Conditioning. These factors are given in Table 7A.1-7A.3 in Annex 7A.1 and are intended to serve as examples of emission rates for developed countries. Only countries with similar systems and regulations or incentives in place should consider using these factors for relevant years.

For mobile air conditioning, emissions can occur during the useful life and during and after disposal of the equipment. Emission sources during the useful life include regular leaks (e.g. from seals), irregular leaks (e.g. due to accidents), and emissions during service (maintenance and refilling). The share of emissions from irregular leaks can be particularly large from passenger cars compared to other mobile vehicles as they are more likely to end up in accidents leading to eruption of the AC system. The default ranges in Table 7.9 encompass emissions from all stages. Several newer studies indicate that annual emission rates for modern passenger cars may be lower than the default lifetime emission factor lower range, e.g. see Schwarz and Harnisch (2003), Japan Automobile Manufacturers Association (2008), Papasavva *et al.* (2009), Clodic *et al.* (2011), Kim and Kim (2014), and Minnesota Pollution Control Agency (2017). However, in most of the studies, the presented emission rates include only regular leaks, or only regular and irregular leaks, excluding emissions during servicing. It is *good practice* to include emissions from all three sources when choosing operating lifetime emission factors.

There are few studies on remaining charge of refrigerants at end-of-life (p) and recovery efficiency (n_{rec}) in equipment, e.g. Kim and Kim (2014), Wimberger (2010), Schwarz (2012), Gallagher, et, al. (2014).

As the practice for mobile A/C service and disposal procedures may vary considerably between countries and over time, inventory compilers should investigate the national circumstances when developing country-specific factors for emissions and recovery efficiency. In some countries, A/C RRR service units (recover/recycle/recharge) are used to significantly reduce emissions at the service and disposal lifecycle stages. This will decrease emission factors during use and increase recovery efficiency (n_{rec}) at end of life. Some countries have started to require recovery of refrigerants at the end-of-life, in which case the recovery efficiency could be higher than the suggested ranges in Table 7.9.

It is *good practise* to consider applying different emission factors in different years to reflect improvements in service and disposal practices and in equipment design and materials. Changes in emission factors over time could also be appropriate for countries that have introduced mandatory periodical inspection and repair regulations/schemes or similar incentives.

Some import and export of used vehicles and end-of-life vehicles occurs between countries (mostly from developed countries to developing countries). It is important for inventory compilers to take into account such flows of MAC equipment when estimating emissions from MAC as it may affect the composition of vehicle stock at various emission stages (lifetime and end-of-life).

TABLE 7.9 (UPDATED)

DEFAULT ESTIMATES[1] FOR CHARGE, LIFETIME AND EMISSION FACTORS FOR REFRIGERATION AND AIR-CONDITIONING SYSTEMS

Sub-application	Charge (kg)	Lifetimes (years)[2]	Emission Factors (% of initial charge/year)[3]		End-of-Life Emission (%)	
Factor in Equation	**(M)**	**(d)**	**(k)**	**(x)**	**($\eta_{rec,d}$)**	**(p)**
			At Time of Charge	**Annual loss, Operating Lifetime**	**Recovery Efficiency[4]**	**Initial Charge Remaining**
Domestic Refrigeration	$0.05 \le M \le 0.5$	$12 \le d \le 20$	$0.2 \le k \le 1$	$0.1 \le x \le 0.5$	$0 < \eta_{rec,d} < 70$	$0 < p < 80$
Stand-alone Commercial Applications	$0.2 \le M \le 6$	$10 \le d \le 15$	$0.5 \le k \le 3$	$1 \le x \le 15$	$0 < \eta_{rec,d} < 70$	$0 < p < 80$
Medium & Large Commercial Refrigeration	$50 \le M \le 2000$	$7 \le d \le 15$	$0.5 \le k \le 3$	$10 \le x \le 35$	$0 < \eta_{rec,d} < 70$	$50 < p < 100$
Transport Refrigeration	$3 \le M \le 8$	$6 \le d \le 9$	$0.2 \le k \le 1$	$15 \le x \le 50$	$0 < \eta_{rec,d} < 70$	$0 < p < 50$
Industrial Refrigeration including Food Processing and Cold Storage	$10 \le M \le 10{,}000$	$15 \le d \le 30$	$0.5 \le k \le 3$	$7 \le x \le 25$	$0 < \eta_{rec,d} < 90$	$50 < p < 100$
Chillers	$10 \le M \le 2000$	$15 \le d \le 30$	$0.2 \le k \le 1$	$2 \le x \le 15$	$0 < \eta_{rec,d} < 95$	$80 < p < 100$
Residential and Commercial A/C, including Heat Pumps	$0.5 \le M \le 100$	$10 \le d \le 20$	$0.2 \le k \le 1$	$1 \le x \le 10$	$0 < \eta_{rec,d} < 80$	$0 < p < 80$
Mobile A/C	$5 \le M \le 6500$ (maritime) $10 \le M \le 30$ (railway) $4 \le M \le 18$ (busses) $0.5 \le M \le 2$ (other MAC)	$9 \le d \le 16$	$0.2 \le k \le 0.5$	$20 \le x \le 40$ (maritime) $5 \le x \le 20$ (railway) $10 \le x \le 20$ (other MAC)	$0 < \eta_{rec,d} < 50$	$0 < p < 50$

Source:

[1] UNEP RTOC Reports (UNEP-RTOC, 1999; UNEP-RTOC, 2003), Japan Refrigeration and Air Conditioning Industry Association (2009), Gallagher et al (2014), Umweltbundesamt (2015). For information on mobile A/C charge and mobile A/C emission factors for annual loss during operating lifetime: Schwarz and Rhiemeier (2007) and Gallagher et al (2014).

[2, 3] Lower value for developed countries and higher value for developing countries

[4] The lower threshold (0%) highlights that there is no recovery in some countries.

7.5.2.3 CHOICE OF ACTIVITY DATA

Tier 1a/b method

Inventory compilers in countries that manufacture refrigerant chemicals should estimate Annual Sales of New Refrigerant using information provided by chemical manufacturers. Data on imported chemical should be collected from customs statistics, importers, or distributors.

Total Charge of New Equipment can be estimated using either:

- Information from equipment manufacturers/importers on the total charge of the equipment they manufacture or import; or
- Information from chemical manufacturers/importers on their sales to equipment manufacturers and distributors.

Ensure this information only includes sales as refrigerant, not feedstock or other uses. The difference between the total sales of new refrigerant and that charged in new equipment is assumed to be used for servicing. Where information on new equipment charges is unavailable, it can be assumed that, in a mature market, two thirds of refrigerant is used for servicing while one third is used for new equipment. However, the adoption of such assumptions must be accompanied by some justification about the state of the market and how well these assumptions are likely to apply.

Tier 2 methods

Both Tier 2a and Tier 2b methods require the development of a matrix for each sub-application based on equipment type on the one hand and refrigerant type on the other hand. In order to derive the number of pieces of equipment for all the vintages, historic net consumption activity data is also required. The annual update of the matrix makes it possible to recalculate all emission types as detailed in Equations 7.10 to 7.14 each year. Moreover, the refrigerant choice has to be assessed on a year-by-year basis owing to changing national regulations (often relating to CFC and HCFC phase-out at different dates) and changing technological choices. In some countries HFC refrigerant regulations have started to enter into force.

Where country-specific data cannot be analysed to this level, globally or regionally validated activity data can be obtained from reputable databases based on refrigerant charges and lifetimes provided in Table 7.9, for all sub-applications, to facilitate Tier 2 methods. A number of refinements are usually necessary dependent on the particular circumstances of the country. Assistance for this can be obtained from application experts.

Other shared issues

Whether collecting country-specific activity data in support of a Tier 1 or a Tier 2 method, inventory compilers must take care in dealing with refrigerant blends. Table 7.8 illustrates the complexity already existing and blends are only expected to increase in popularity as manufacturers of equipment seek for further improvements in performance, particularly in respect of energy efficiency. Where blends contain both HFCs and other components, only the reportable elements need to be considered. This is even the case for other components with significant GWPs (e.g., CFCs and HCFCs).

Inventory compilers also need to consider how to monitor the movement of trade in equipment and products containing HFCs and/or PFCs. The Box 7.3 below sets out some of the measures required to estimate imports and exports adequately.

BOX 7.3
ACCOUNTING FOR IMPORTS AND EXPORTS OF REFRIGERANT AND EQUIPMENT

In estimating *Annual Sales of New Refrigerant*, *Total Charge of New Equipment*, and *Original Total Charge of Retiring Equipment*, as required for Tier 2b, inventory compilers should account for imports and exports of both chemicals and equipment. This will ensure that they capture the actual domestic consumption of chemicals and equipment. For example, if a country imports a significant share of the HFC-134a that it uses, the imported quantity should be counted as part of **Annual Sales**. Alternatively, if a country charges and then exports a significant number of household refrigerators, the total charge of the exported refrigerators should be subtracted from the total charge of the household refrigerators manufactured in the country to obtain **Total Charge of New Equipment**.

GENERAL APPROACH: In general, the quantity Annual Sales should be estimated using the following formula:

Annual Sales = Domestically Manufactured Chemical
+ Imported Bulk Chemical
- Exported Bulk Chemical
+ Chemical Contained in Factory-Charged Imported Equipment
- Chemical Contained in Factory-Charged Exported Equipment

All quantities should come from the year for which emissions are being estimated. Similarly, the quantity of **Total Charge of New Equipment** should be estimated using the following:

Total Charge of New Equipment
= Chemical to Charge Domestically Manufactured Equipment that is not Factory-Charged
+ Chemical to Charge Domestically Manufactured Equipment that is Factory-Charged
+ Chemical to Charge Imported Equipment that is not Factory-Charged
+ Chemical Contained in Factory-Charged Imported Equipment
- Chemical Contained in Factory-Charged Exported Equipment

Original Total Charge of Retiring Equipment should be estimated the same way as *Total Charge of New Equipment*, except all quantities should come from the year of manufacture or import of the retiring equipment.

SIMPLIFIED APPROACH: In estimating *Annual Sales* and *Total Charge of New Equipment*, it is possible to ignore the quantities of chemical imported or exported inside of factory-charged equipment if these quantities cancel out in the calculation of emissions. However, inventory compilers that use the simplified calculation should ensure that: (1) they treat imports and exports of factory-charged equipment consistently in estimating both *Annual Sales* and *Total Charge New of Equipment*; and (2) they continue to account for imports and exports of factory-charged equipment in estimating *Original Total Charge of Retiring Equipment*. As new equipment will eventually become retiring equipment, countries may wish to track imports and exports of factory-charged equipment even if this information is not strictly necessary to develop the current year's estimate.

The simplified formula for **Annual Sales** is:

Annual Sales = Domestically Manufactured Chemicals
+ Imported Bulk Chemicals
- Exported Bulk Chemicals

The simplified formula for **Total Charge of New Equipment** is:

Total Charge of New Equipment
= Chemicals to Charge Domestically Manufactured Equipment
+ Chemical to Charge Imported Equipment that is not Factory-Charged

The full formula, accounting for imports and exports of pre-charged equipment, must be used to calculate *Original Total Charge of Retiring Equipment*.

BOX 7.3A (NEW)
COMMON DATA SOURCES FOR THE HFC INVENTORY

This box provides a short description of common data sources for the HFC inventory, complementing Table 7.10 in the *2006 IPCC Guidelines*. Examples of data are production, imports, exports and destruction of HFC and equipment containing HFC. Numbers of equipment units and growth rates in sales are also data commonly collected.

Governmental reports

Most countries have collected data for Refrigerant Management Plans (RMPs) or HCFC Phase-out Management Plans (HPMPs) through ODS-alternatives surveys. The consumption data generally contain information on:

- total past consumption of CFCs, and total current and past consumption of HCFCs and possibly also HFCs. Data on ODS are often given in ODP tonnes, which can be converted into metric tonnes using the substance-specific ODP values;

- sector-specific consumption of HCFCs and possibly also HFCs (e.g. amounts used in air conditioning, refrigeration, fire extinguishers, aerosols etc.);

- breakdown of HCFCs according to their use at each lifecycle stage such as manufacturing/assembly (initial charge) or servicing (refill)

Some countries have begun monitoring HFC consumption due to the inclusion of HFCs in the Montreal protocol. Countries that have ratified the Kigali amendment to the Montreal Protocol will be required to report consumption data on HFCs (production, import and export) annually.

European Member States report annually to the European Commission on production and imports of HFCs in bulk, in line with the EU F-Gas Regulation.

Surveys

There is often a limited number of companies producing, importing and exporting HFC in bulk; hence a way to obtain high quality data is to ask the producers, importers, and exporters for information. They should be able to provide information on the amount of gas they produce, import, or export in a certain year. In addition, they may be able to indicate the equipment types in which each HFC or blend is used.

The number of companies importing equipment containing HFC can be large, and surveying this might be resource intensive. If this is the case, other data sources such as sales statistics or national customs registers (see below) may be used instead.

Surveys can also be a way to obtain information on HFC from end-users. Generally, this requires good knowledge of the market and preparatory market research may be needed before launching a survey.

Surveys can also be a way to discover areas and applications previously unknown to the inventory compilers.

National Customs Registers

National Customs Registers contain information on imports and exports of chemicals and equipment potentially containing HFC. If the HFC are subject to tax, such a register might provide the amounts of refrigerant contained in the products. If not, it will probably be necessary to make assumptions regarding the identities and amounts (charge sizes) of HFCs in different types of equipment, multiplying the charge size by the number of equipment units of each type to obtain the total amount of that HFC imported.

BOX 7.3A (NEW) (CONTINUED)
COMMON DATA SOURCES FOR THE HFC INVENTORY

Other national registers

Many countries have national registers of cars uses for taxation purposes. This data source might provide figures on the number of cars, and possibly other information like age and size.

National Product Register/European Chemical Agency: In some countries, a national Products Register is used to store information on chemical products (including HFC) that are manufactured in or transferred or imported into the country and information on the ways in which these are being used.

Industrial organizations

Industrial organizations or trade associations often have statistics on mass-produced types of equipment, like numbers of household refrigerators, small air conditioning units, heat pumps and cars.

If not, they might help with assessments of the size of markets, and hence the consumption figures. It is often challenging to get information on the number of large refrigeration and air conditioning systems. Industrial organizations might provide useful information like annual growth in sales of equipment and average charge size of various types of equipment.

National statistics

Many countries have national offices publishing annual statistics with useful information, like the stock of vehicles and buildings (number or area by type of building), or production of commodities.

7.5.2.4 APPLYING TIER 2 METHODS – THE EXAMPLE OF MOBILE AIR CONDITIONING (MAC)

The Box 7.4 below sets out the step-by-step approach required to assess the emissions from the mobile air conditioning sub-application of a hypothetical country's inventory. The method adopted is primarily a Tier 2a approach, although there are also elements which would be equally applicable to Tier 2b. This example, therefore, highlights the reality that pure approaches and methods are rare in practice. There will often be a mix of emission-factor approach and mass-balance approach as well as a mix of country-specific data and globally or regionally derived data. As pointed out in Section 7.1.2.1, one method, approach or dataset will often be used to cross-check another. This example also demonstrates that a detailed implementation of the Tier 2a method requires a significant amount information gathering about a sub-application. Once established, it is less burdensome to implement the approach in subsequent years. Also note that assumptions made are for example only; inventory compilers should collect country-specific information rather than using the assumptions shown.

BOX 7.4 (UPDATED)

EXAMPLE OF THE APPLICATION OF A TIER 2A CALCULATION FOR MOBILE AIR CONDITIONING

Introduction

National inventories and other studies to date show that emissions of HFC-134a from mobile air conditioners (MACs) contribute significantly to the Refrigeration and Air Conditioning (RAC) Application emissions and the ODS Substitutes Category emissions. For many countries, emissions from MACs will comprise 50 percent or more of the RAC emissions and possibly more than 50 percent of the total ODS Substitutes Category emissions. This is due to many factors, including:

- The phaseout of ODSs to HFCs in MACs occurred earlier and more quickly than other Sub-Applications, such as residential (stationary) air conditioning and commercial refrigeration (supermarkets), which still rely substantially on ODSs.
- MACs are subject to extremes in terms of physical shock and vibration and hence emissions tend to be large.
- The lifetime of MACs tends to be shorter than many other RAC Sub-Applications, so that end-of-life emissions are seen earlier and equipment stocks relying on ODSs are replaced sooner with HFCs.
- Due to the small charge of refrigerant involved, recovery from MACs is often seen as uneconomical and hence is not often practiced during service and disposal.

In addition, data on vehicle purchases and registrations in a country are often known to a higher degree of quality or are easily obtained. Hence, it is *good practice* to estimate emissions from this Sub-Application. The following text describes how the general equations for the RAC Application can be applied to the MAC Sub-Application.

Data Gathering and Assumptions

An accurate estimate of MAC emissions may be obtained by collecting some data at the Sub-Application level and applying a few basic assumptions to simplify the data and calculations required, as follows:

Refrigerant Type. It will be important to separate each data point by refrigerant, so that emissions of each refrigerant are calculated separately. For MACs, this may be simplified by the fact that all MACs produced since the mid- to late-1990s use HFC-134a as the refrigerant. However, CFC-12 was used in the past and still exists in some operating systems. Furthermore, for the future other refrigerants such as HFC-152a and R-744 (carbon dioxide) are being considered.

Refrigerant Sold in Containers (RM_t). For MACs, refrigerant generally comes in three basic types of containers – ‘bulk containers’ sent to vehicle manufacturers to fill new MACs, ‘small cans’ containing about 300-500 grams of refrigerant generally used by individuals servicing their own equipment, and ‘cylinders’ containing about 10-15 kilograms of refrigerant used by shops that service many vehicles. If one assumes no losses from bulk containers (see below), then in order to calculate $E_{containers}$, one needs to know the total refrigerant sold in small cans (RM_{sc}) and cylinders (RM_{cy}). It will be important to distinguish the refrigerant sold into different Sub-Applications (e.g., HFC-134a is also used in the chillers and domestic refrigeration Sub-Applications) so that only the refrigerant sold for MACs is used in the calculations. This data may be obtained from small can packagers and refrigerant producers/distributors.

Container Heels (c). For this example, we assume the heels from service containers are not recovered (e.g., the cylinders are discarded, not reused) and are c_{sc} = 20 percent for the small can and c_{cy} = 2 percent for the cylinder. Because bulk refrigerant containers generally go back to the refrigerant producer and are refilled, we can assume there are no heels that would be emitted and hence c_{bulk} = 0 percent.

BOX 7.4 (UPDATED) (CONTINUED)
EXAMPLE OF THE APPLICATION OF A TIER 2A CALCULATION FOR MOBILE AIR CONDITIONING

MACs Produced Each Year (N_t). If the number of MACs placed in service each year is not known, an estimate can be made by multiplying the number of cars placed in service each year by an estimate of the percentage that were sold with MACs. These data may be available from automobile manufacturers, MAC producers/suppliers, or government agencies involved in transportation, infrastructure and highway safety. If more than one type of refrigerant is used, it is important to separate each Nt into the different refrigerants, e.g., $N_{1994} = N_{1994,CFC\text{-}12} + N_{1994,HFC\text{-}134a}$.

Nominal Charge of Each MAC (m_t). This factor would likely vary by the type of vehicle; for instance small passenger cars will likely have lower refrigerant charges than buses or larger cars, especially those with multiple evaporators. Likewise, this could vary over time, for instance decreasing as manufacturers make smaller systems for the same vehicle size, or increasing as larger cars and more multiple-evaporator units enter the market. For this example, we assume a constant over time at an average m = 0.7 kg, which is typical of small to medium-sized passenger cars.

Refrigerant Charged into New Equipment (M_t). This is easily calculated as $M_t = N_t \bullet m_t = 0.7 \bullet N_t$.

Assembly Losses (k). This is used to calculate the Charge Emissions, also referred to as 'First-Fill Emissions.' The loss rate is often small, on the order of k = 0.5 percent or smaller. For simplicity, we assume k = 0 in this example.

Lifetime (d). The presumed lifetime of a MAC. This variable can be based on national data and can be different for different types of MACs (passenger cars, buses, etc.) For this example, we assume the lifetime of all MACs is d = 12 years.

Bank in Existing Equipment (B). The bank will be the amount of refrigerant in MACs put into service, minus the amount of refrigerant in MACs disposed, plus the amount of refrigerant used to service MACs, minus the amount that has leaked. In actuality, a given MAC will probably leak over several years before being serviced. Rather than attempting to account for this, for this example we apply Equation 7.13 which assumes all MACs are serviced each year such that the estimated charge of each MAC is the same as the nominal charge. The annual emission rate is averaged to account for this assumption. This will only produce small errors unless the year-to-year sales of MACs fluctuate widely. Hence the bank in any given year is the sum of the Refrigerant Charged into New Equipment each year from the current year back to the assumed average lifetime of the equipment. Thus,

$$B_t = \sum_{i=1}^{d} M_{t-i+1}$$

For example, using d = 12 years, the bank in 2006 would be $B_{2006} = M_{2006} + M_{2005} + M_{2004} + \ldots + M_{1997} + M_{1996} + M_{1995}$.

Annual Emission Rate (x). This factor accounts for both leaks from equipment as well as any emissions during service. Both of these items can be different for different types of MACs and can also vary by when the MAC was produced (i.e., older MACs may leak more than newer MACs). If annual servicing does not occur, the amount emitted at any servicing event needs to be average over the number of years between servicing event to obtain the annual rate. This amount is likely to vary considerably depending on national conditions and what type(s) of service is (are) performed. Whether recovery of the given charge before service is performed must be considered, and may be deduced in part by examining the amount of refrigerant sold in small cans versus cylinders. For this example, we assume that 15 percent of the nominal charge is leaked each year and 5 percent on average is emitted during servicing. Hence, x = 20 percent.

Residual Charge in MACs Disposed (p). Assuming that the MAC is serviced the year before it is disposed, and that the annual nominal charge is estimated, this is easily calculated as p = 1 – nominal charge. In our example, p = 1 – 15 % = 0.85.

BOX 7.4 (UPDATED) (CONTINUED)
EXAMPLE OF THE APPLICATION OF A TIER 2A CALCULATION FOR MOBILE AIR CONDITIONING

Recovery Efficiency $(nrec)$. If no regulations or incentives exist to require recovery of refrigerant from MACs disposed, then likely very little will occur. So, for this example, we assume that nrec = 0.

Calculation of Different Types of Emissions

Now that these data have been gathered and assumptions have been made, calculating the emissions may be performed. An example for year t = 2006 follows:

Container Emissions (Equation 7.11).

$$E_{containers,2006} = RM_{cy,2006} \bullet c_{cy} + RM_{sc,2006} \bullet c_{sc} = 0.02 \bullet RM_{cy,2006} + 0.2 \bullet RM_{sc,2006}$$

Charging Emissions (Equation 7.11).

$$E_{charge,2006} = M_{2006} \bullet k = 0$$

Lifetime (Operating and Servicing) Emissions (Equation 7.13).

$$\begin{aligned} E_{operation,2006} &= B_{2006} \bullet x = 0.20 \bullet B_{2006} = 0.20 \bullet \sum_{i=1}^{d} M_{t-i+1} \\ &= 0.20 \bullet (M_{2006} + M_{2005} + M_{2004} + \cdots + M_{1997} + M_{1996} + M_{1995}) \\ &= 0.20 \bullet m \bullet (N_{2006} + N_{2005} + N_{2004} + \cdots + N_{1997} + N_{1996} + N_{1995}) \\ &= 0.20 \bullet 0.7 \bullet (N_{2006} + N_{2005} + N_{2004} + \cdots + N_{1997} + N_{1996} + N_{1995}) \\ &= 0.14 \bullet (N_{2006} + N_{2005} + N_{2004} + \cdots + N_{1997} + N_{1996} + N_{1995}) \end{aligned}$$

End-of-Life Emissions (Equation 7.14).

$$\begin{aligned} E_{end-of-life,2006} &= M_{2006-d} \bullet p \bullet (1 - n_{rec}) = M_{2006-12} \bullet 0.85 \bullet (1-0) \\ &= 0.85 \bullet M_{1994} = 0.85 \bullet 0.7 \bullet N_{1994} = 0.595 \bullet N_{1994} \end{aligned}$$

Calculation of Total Emissions

Total MAC Emissions (Equation 7.10).

$$\begin{aligned} E_{total,2006} &= E_{containers,2006} + E_{charge,2006} + E_{lifetime,2006} + E_{servicing,2006} + E_{end-of-life,2006} \\ &= 0.02 \bullet RM_{cy,2006} + 0.2 \bullet RM_{sc,2006} + 0 \\ &\quad + 0.14 \bullet (N_{2006} + N_{2005} + N_{2004} + \cdots + N_{1997} + N_{1996} + N_{1995}) + 0.595 \bullet N_{1994} \\ &= 0.02 \bullet RM_{cy,2006} + 0.2 \bullet RM_{sc,2006} \\ &\quad + 0.14 \bullet (N_{2006} + N_{2005} + N_{2004} + \cdots + N_{1997} + N_{1996} + N_{1995}) + 0.595 \bullet N_{1994} \end{aligned}$$

The only unknowns are:

- RM_{sc} – refrigerant (in kilograms) sold in small cans to service MACs, which may be obtained from small can packagers;
- RM_{cy} – refrigerant (in kilograms) sold in cylinders to service MACs, which may be obtained from refrigerant producers/distributors; and,
- N_t – the number of MACs put in service each year, which may be available from automobile manufacturers, MAC producers/suppliers, or government agencies involved in transportation, infrastructure and highway safety.

BOX 7.4 (UPDATED) (CONTINUED)
EXAMPLE OF THE APPLICATION OF A TIER 2A CALCULATION FOR MOBILE AIR CONDITIONING

If the emissions from refrigerant containers and from end-of-life are not included, for example if it is believed that service cylinders are completely evacuated and minimal MACs reach their end-of-life in the given year, this equation becomes simply an activity (the number of MACs) multiplied by an emission factor (annual emission rate times average charge size, in this case 0.14 kg per MAC). This calculation yields the total emissions in kilograms of refrigerant. Keeping each refrigerant separate and multiplying each sum by the refrigerant's GWP will yield kilograms of CO_2 equivalent emissions. Dividing by 1 billion (10^9) will yield emissions in teragrams of CO_2 equivalent ($TgCO_2eq$).

7.5.2.5 COMPLETENESS

No refinement.

7.5.2.6 DEVELOPING A CONSISTENT TIME SERIES

No refinement.

7.5.3 Uncertainty assessment

No refinement.

7.5.4 Quality Assurance/Quality Control (QA/QC), Reporting and Documentation

No refinement.

7.6 FIRE PROTECTION

No refinement.

7.7 OTHER APPLICATIONS

No refinement.

Annex 7A.1 (New) Examples of national studies on emission rates for stationary refrigeration and air-conditioning systems

The three sets of emission factors presented below are intended to serve as examples of emission rates (and in one case recovery efficiency at end-of-life) for stationary refrigeration and air-conditioning systems. Only countries with similar systems and regulations or incentives in place should consider using these factors for relevant years. In each table, the IPCC sub-application (found in Table7.9) are amended for the purpose of reference.

TABLE 7A.1 (NEW)
CALIFORNIA STUDY FOR 2008: EMISSION FACTORS FOR STATIONARY REFRIGERATION AND AIR-CONDITIONING SYSTEMS

Equipment Type or Emission Sub-application	**Annual loss, Operating Lifetime Emission Factors (% of initial charge/year)**	**Recovery Efficiency, End-of-Life Emission (%)**	**IPCC Sub-application**
Factor in Equation	**(x)**	**(nrec,d)**	
Refrigeration Large Centralized System ≥ 907.2 kg (2,000 lbs.)	21.0%	80%	Medium & Large Commercial Refrigeration
Refrigeration Medium Centralized System 90.7-< 907.2 kg (200-< 2,000 lbs.)	15.0%	80%	Medium & Large Commercial Refrigeration
AC Large Centrifugal Chiller ≥ 907.2 kg (2,000 lbs.)	2.4%	80%	Chillers
AC Medium Centrifugal Chiller 90.7-< 907.2 kg (200-< 2,000 lbs.)	1.4%	80%	Chillers
AC Chiller - Packaged 90.7-< 907.2 kg (200-< 2,000 lbs.)	6.9%	80%	Chillers
Refrigeration Large Cold Storage ≥ 907.2 kg (2,000 lbs.)	21.6%	84%	Industrial Refrigeration including Food processing and Cold Storage
Refrigeration Medium Cold Storage 90.7-< 907.2 kg (200-< 2,000 lbs.)	28.8%	84%	Industrial Refrigeration including Food processing and Cold Storage
Refrigeration Process Cooling ≥ 907.2 kg (2,000 lbs.)	6.8%	80%	Industrial Refrigeration including Food processing and Cold Storage
Refrigerated Condensing units 22.7-≤ 90.7 kg (50-≤ 200 lbs.)	14.5%	80%	Medium & Large Commercial Refrigeration
Unitary AC 22.7-≤ 90.7 kg (50-≤ 200 lbs.)	11.3%	80%	Residential and Commercial A/C, including Heat Pumps
Refrigerated Condensing Units ≤ 22.7 kg (50-lbs. or less)	15%	66%	Medium & Large Commercial Refrigeration
Unitary A/C ≤ 22.7 kg (50-lbs. or less) (central)	10%	44%	Residential and Commercial A/C, including Heat Pumps
Unitary A/C ≤ 22.7 kg (50-lbs. or less) (window unit)	2%	0%	Residential and Commercial A/C, including Heat Pumps

TABLE 7A.1 (NEW) (CONTINUED)
CALIFORNIA STUDY FOR 2008: EMISSION FACTORS FOR STATIONARY REFRIGERATION AND AIR-CONDITIONING SYSTEMS

Equipment Type or Emission Sub-application	Annual loss, Operating Lifetime Emission Factors (% of initial charge/year)	Recovery Efficiency, End-of-Life Emission (%)	IPCC Sub-application
Factor in Equation	**(x)**	**(nrec,d)**	
Residential Appliance (refrigerator-freezer)	1%	33%	Domestic Refrigeration
Transport Refrigerated Units (TRUs)	18.3%	85%	Transport Refrigeration
Refrigerated Shipping Containers	5%	81%	Transport Refrigeration

Source: Gallagher et al (2014).

TABLE 7A.2 (NEW)
JAPAN STUDY FOR 2008: EMISSION FACTORS FOR STATIONARY REFRIGERATION AND AIR-CONDITIONING SYSTEMS

Equipment Type or Emission Sub-application		Annual loss, Operating Lifetime Emission Factors (% of initial charge/year)	IPCC Sub-application
Factor in Equation		**(x)**	
Large Refrigerators-freezers	Centrifugal refrigerating machine	7%	Chillers
	Screw refrigerating machine	12%	Industrial Refrigeration including Food Processing and cold storage
Medium Refrigerators-freezers	Transport refrigerator-freezer unit	15%	Transport Refrigeration
	Refrigerator-freezer unit	17%	Medium&Large Commercial Refrigeration
	Condensing unit	13%	Medium&Large Commercial Refrigeration
	Separately placed showcase	16%	Medium&Large Commercial Refrigeration
Commercial air-conditioning equipment	PAC (Package air-conditioning) for store	3%	Residential and Commercial A/C, including Heat Pump
	PAC (Package air-conditioning) for building	3,5%	Residential and Commercial A/C, including Heat Pump
	PAC (Package air-conditioning) for industry	4,5%	Residential and Commercial A/C, including Heat Pump
	GHP	5,0%	Residential and Commercial A/C, including Heat Pump
Room air-conditioning		2%	Residential and Commercial A/C, including Heat Pump
Small Refrigerators-freezers	All-in-one type (e.g. built-in showcase, ice making machinery, water fountain, commercial refrigerator)	2%	Stand-alone Commercial Application
Chilling unit	Chilling unit (e.g. chilling unit for refrigerator-freezer, chilling unit for air-conditioning)	6%	Chillers

Source: Nomura Research Institute, Ltd. (2012).

TABLE 7A.3 (NEW)
GERMAN STUDY FOR 2009-2013: EMISSION FACTORS FOR STATIONARY REFRIGERATION AND AIR-CONDITIONING SYSTEMS

Equipment Type or Emission Sub-application	Annual loss, Operating Lifetime Emission Factors (% of initial charge/year)
Factor in Equation	**(x)**
Medium & Large Commercial Refrigeration (centralized)	7.64 – 10.02
Small Commercial Refrigeration (condensing units)	3.09 -5.18
Industrial Refrigeration including Food Processing and Cold Storage	4.71
AC Chiller	3.39
AC Multisplit/VRF (Variable Refrigerant Flow)	3.80

Source: Umweltbundesamt (2015)

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CHAPTER 8

OTHER RODUCT MANUFACTURE AND USE

Authors

Section 8.3

Michael Roger Czerniak (UK), Sébastien Raoux (France/USA) and Andrea Zille (Italy/Portugal)

Appendix 1 to Volume 3

Sébastien Raoux (France/USA) and Andrea Zille (Italy/Portugal)

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8 OTHER PRODUCT MANUFACTURE AND USE

Users are expected to go to Mapping Tables in Annex 5, before reading this chapter. This is required to correctly understand both the refinements made and how the elements in this chapter relate to the corresponding chapter in the 2006 IPCC Guidelines.

8.1 INTRODUCTION

No refinement.

8.2 EMISSIONS OF SF_6 AND PFCs FROM ELECTRICAL EQUIPMENT

No refinement.

8.3 USE OF SF_6 AND PFCs IN OTHER PRODUCTS

8.3.1 Introduction

This source category excludes the following source categories that are addressed elsewhere in the *2006 IPCC Guidelines*:

- Production of SF_6 and PFCs (Section 3.10);
- Production and use of electrical equipment (Section 8.2);
- Primary and secondary production of magnesium and aluminium (Chapter 4); and
- Semiconductor and flat panel display manufacturing (Chapter 6).

Identified remaining applications in this source category include:

- SF_6 and PFCs used in military applications, particularly SF_6 used in airborne radar systems, e.g., Airborne Warning and Control System (AWACS), and PFCs used as heat transfer fluids in high-powered electronic applications;
- SF_6 used in equipment in university and research particle accelerators;
- SF_6 used in equipment in industrial and medical particle accelerators;
- 'Adiabatic' applications utilising the low permeability through rubber of SF_6 and some PFCs, e.g., car tires and sport shoe soles;
- SF_6 used in sound-proof windows;
- PFCs used as heat transfer fluids in commercial and consumer applications;
- PFCs used in cosmetics and in medical applications;
- Other uses e.g. gas-air tracer in research and leak detectors.
- PFCs and other fluorinated compounds in the manufacturing of textiles and waterproofing of electronic circuits

8.3.2 Methodological issues

8.3.2.1 CHOICE OF METHOD

The *good practice* method is to use either consumption data from users of SF_6 or PFCs or top-down import, export and consumption data from national SF_6 producers and distributors, disaggregated by major type of SF_6 or

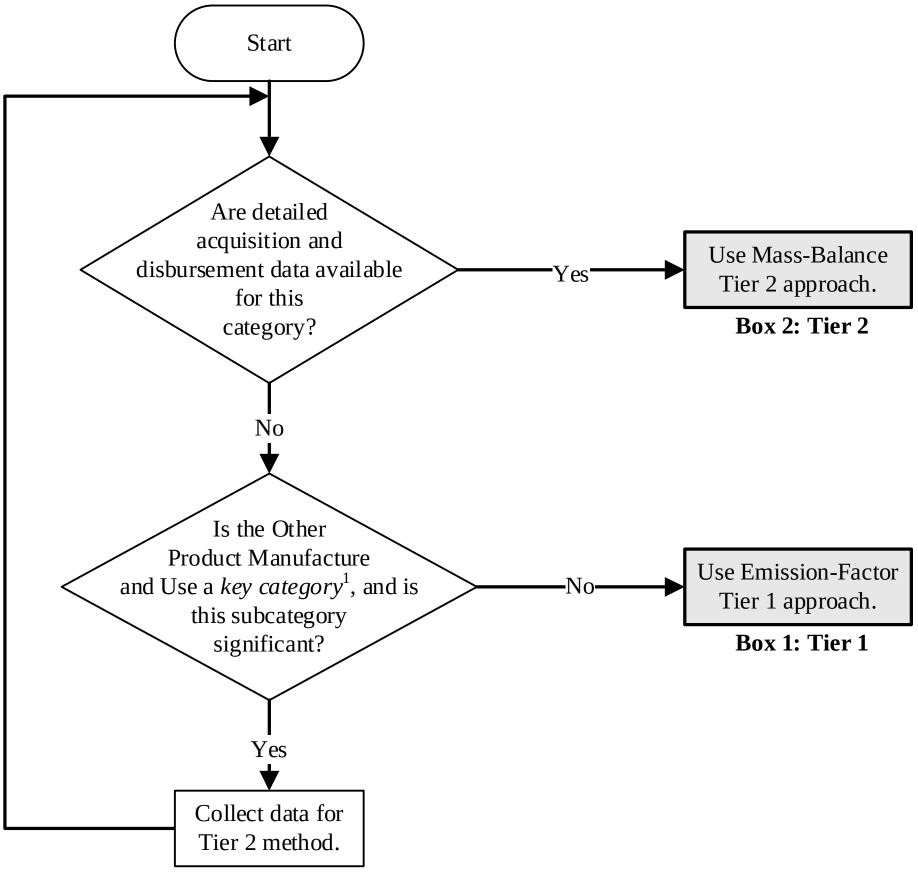
PFC application. Acquiring this data will entail a survey of all producers and distributors of SF_6 and PFCs to identify total net SF_6 and PFC consumption. Once the data are obtained, the amount of SF_6 and PFC consumed by application in this source category should be estimated.

MILITARY APPLICATIONS

SF_6 EMISSIONS FROM OPERATION OF AWACS

SF_6 is used as an insulating medium in the radar systems of military reconnaissance planes of the Boeing E-3A type, commonly known as AWACS. The purpose of the SF_6 is to prevent electric flashovers in the hollow conductors of the antenna, in which high voltages of more than 135 kV prevail. When the plane ascends, SF_6 is automatically released from the system and into the atmosphere to maintain the appropriate pressure difference between the system and the outside air. When the plane descends, SF_6 is automatically charged into the system from an SF_6 container on board. Most emissions occur during the pressure-balancing process on ascent, but emissions from system leakage can also occur during other phases of flight or during time on the ground. Annual emissions per plane have been estimated to be 740 kg, while the charge of each system is approximately 13 kg.

Figure 8.2 Decision tree for SF_6 from AWACS



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.

Tier 1 method – SF_6 emissions per plane

If a country does not have data on SF_6 consumption by its AWACS, it may use a per-plane emission factor to estimate emissions. An emission factor of 740 kg per plane per year is presented in Table 8.7 below; this figure is based on estimates of SF_6 emissions from NATO Boeing E-3As. Note that actual emissions per plane are strongly influenced by the average number of sorties (take-offs) per plane per year. More frequent sorties will raise the emission rate above 740 kg/plane; less frequent sorties will lower it. Leakage rates during flight or during time on the ground will also affect the emission rate.

EQUATION 8.12
EMISSIONS FROM AWACS (DEFAULT EMISSION ACTOR)

$$User\ Emissions\ =\ 740\ kg \bullet Number\ of\ planes\ in\ AWACS\ fleet$$

TABLE 8.7
SF_6 EMISSIONS PER PLANE PER YEAR

Emissions per plane per year (kg SF_6)	Uncertainty
740 kg	±100 kg
Source: Schwarz (2005)	

Table 8.8 includes information on national AWACS fleets worldwide (Boeing, 2005); like other activity data, it may quickly go out of date. Countries are in the best position to know the numbers of planes in their AWACS fleets.

TABLE 8.8
NATIONAL AWACS FLEETS

Country/ Organisation	USA	Japan	France	UK	Other NATO	Saudi Arabia	Total
No. AWACS	33	4	4	7	17	5	70
Source: Boeing (2005)							

Tier 2 method – user mass-balance method

The most accurate method for estimating SF_6 emissions from AWACS is to track SF_6 consumption by the systems. To do so, the following equations, which are similar to the utility-level variant of the Tier 3 method for electrical equipment, may be used. Note that for AWACS, acquisitions and disbursements of SF_6 containers are likely to be considerably more important to the result than acquisitions and retirements of operating systems.

EQUATION 8.13
EMISSIONS FROM AWACS (USER MASS-BALANCE)

$$\begin{aligned} User\ Emissions\ &=\ Decrease\ in\ SF_6 Inventory\ +\ Acquisitions\ of\ SF_6 \\ &-\ Disbursements\ of\ SF_6 -\ Net\ Increase\ in\ AWACS\ Fleet\ Charge \end{aligned}$$

Where:

Decrease in SF_6 Inventory = SF_6 stored in containers at the beginning of the year – SF_6 stored in containers at the end of the year

Acquisitions of SF_6 = SF_6 purchased from chemical producers or distributors in bulk + SF_6 purchased from AWACS manufacturers or distributors with or inside of new planes + SF_6 returned to site after off-site recycling

Disbursements of SF_6 = SF_6 contained in AWACS that are transferred to other entities + SF_6 returned to suppliers + SF_6 sent off-site for recycling + SF_6 destroyed

Net Increase in AWACS Fleet Charge = 13 kg • (New AWACS – Retiring AWACS)

SF_6 AND PFC EMISSIONS FROM OTHER MILITARY APPLICATIONS

There is wide range of military applications using PFCs or SF_6.[1] Military electronics are believed to be an important and growing application of PFC heat transfer fluids, which are valued for their stability and dielectric properties. The fluids are used in ground and airborne radar (klystrons), avionics, missile guidance systems, Electronic Counter Measures (ECM), sonar, amphibious assault vehicles, other surveillance aircraft, lasers, SDI (Strategic Defense Initiative), and stealth aircraft. PFCs may also be used to cool electric motors, particularly in applications where noise reduction is valued, e.g., in ships and submarines. The specific PFCs used in these applications are believed to be similar to those identified as heat transfer fluids in electronics manufacturing in Chapter 6. Spray cooling, jet impingement cooling, and pool boiling appear to be the favoured systems for heat removal. In all of these cooling applications, the PFC is contained in a closed system, and neither replacement nor replenishment of the PFC liquid appears to be required. Thus, the greatest opportunities for emissions are the manufacture, maintenance, and, especially, the disposal of the equipment.

SF_6 is used in high-performance ground and airborne radar systems in their hollow conductors for transmission of high-frequency energy pulses at high voltages from the klystron. Another application of SF_6 is as an oxidant of lithium in Stored Chemical Energy Propulsion System (SCEPS), e.g., in naval torpedoes and in infrared decoys (Koch, 2004). Apparently, these applications of SF_6, like those of the PFC heat transfer fluids enumerated above, are generally more or less enclosed, but servicing and testing procedures may lead to emission. The use of SF_6 for the quieting of torpedo propellers has also been reported (NIST, 1997).

In addition, SF_6 may be emitted as a by-product of the processing of nuclear material for the production of fuel and nuclear warheads. SF_6 is known to be emitted from neutralising excess fluorine during the production of nuclear fuel for civilian applications (AREVA, 2005).

Although it is believed that the total amounts of SF_6 and PFCs consumed and emitted in this sector may be significant, no data on quantities are publicly available so far. Therefore, inventory compilers should try to collect further information from the relevant authorities and, if possible, their suppliers. As noted above, the greatest opportunities for emissions from many of these applications appear to be the manufacture, maintenance, and disposal of the equipment. Thus, if inventory compilers can acquire information on emission rates during the manufacture, maintenance, and disposal of the equipment, along with the quantities of equipment manufactured, in use, and disposed, they can use the Tier 2 or Tier 3 method for electrical equipment to estimate emissions. For applications with different emissions profiles (e.g., prompt emissions), the appropriate equation from Section 8.2 may be used.

SF_6 EMISSIONS FROM UNIVERSITY AND RESEARCH PARTICLE ACCELERATORS

SF_6 is used in university and research operated particle accelerators as an insulating gas. Typically, high voltage equipment is contained and operated within a vessel filled with SF_6 at a pressure exceeding atmospheric pressure. Charges range from five kilograms to over ten thousand kilograms, with typical charges falling between 500 and 3 000 kg. When the equipment requires maintenance, the SF_6 is transferred into storage tanks. SF_6 losses occur primarily during gas recovery and transfer, when pressure relief valves are actuated, and through slow leaks.

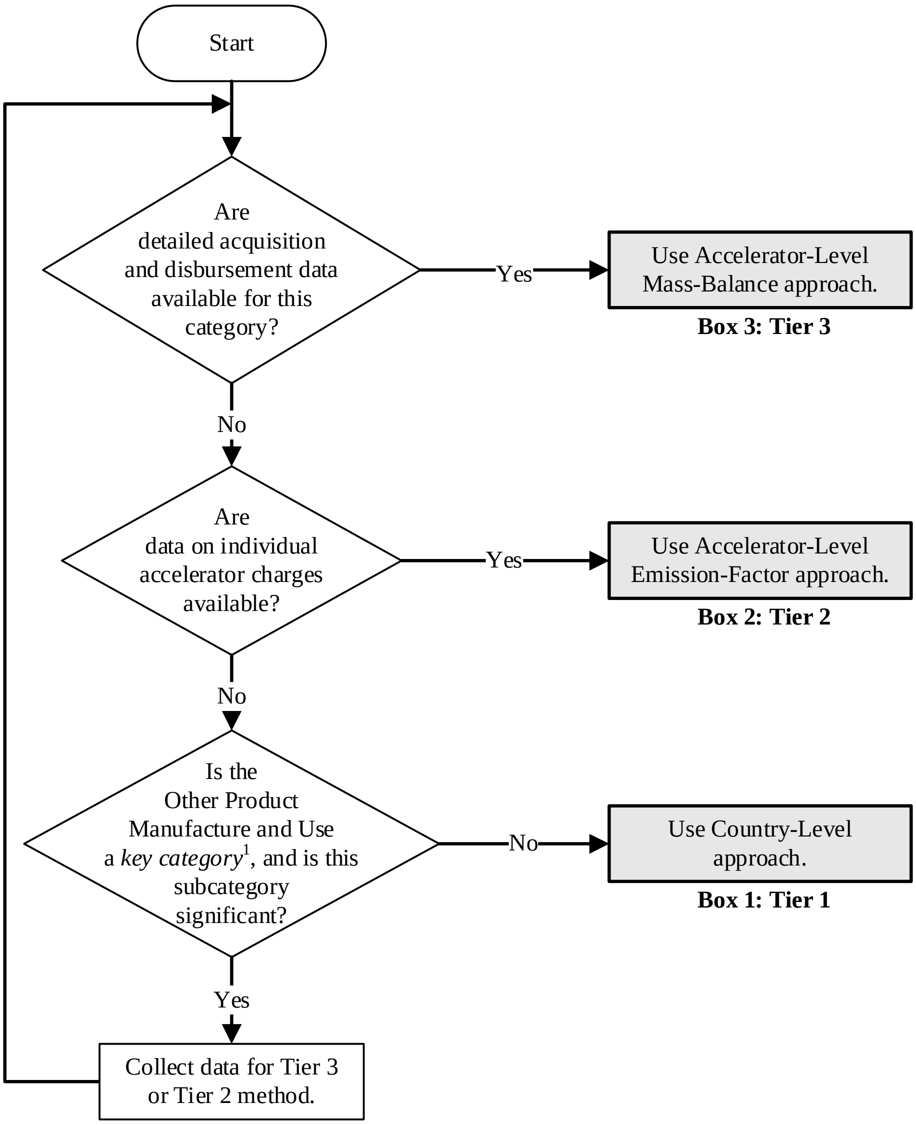
Based on two recent studies annual SF_6 losses range between 5 and 7 percent of vessel capacity per year and generally depend on the vessel opening frequency plus the efficiency of the recovery and transfer equipment. World banked capacity is roughly estimated to be 500 tonnes with annual SF_6 emissions of 35 tonnes.

Switzerland has developed a voluntary program to reduce SF_6 emissions from particle accelerators. Suggestions and techniques for reducing SF_6 emissions from these sources exist.

---

[1] David Harris and James Hildebrandt, “Spray Cooling Electrical and Electronic Equipment,” *COTS Journal*, November 2003; C. Shepherd Burton, “Uses and Air Emissions of Liquid PFC Heat Transfer Fluids from the Electronics Sector,” Draft report prepared for Scott C. Bartos, U.S. Environmental Protection Agency.

Figure 8.3 **Decision tree for SF_6 from research accelerators**



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.

Tier 1 method – country-level method

In cases where individual user accelerator charge data is unavailable, one extremely rough method involves determining the total number of university and research particle accelerators in the country and using several factors to determine the country-level annual emission rate as noted in Equation 8.14. For this Tier 1 method, the only data that requires collection is the total number of university and research particle accelerators in the given country.

EQUATION 8.14

UNIVERSITY AND RESEARCH PARTICLE ACCELERATOR EMISSIONS (COUNTRY-LEVEL)

$$\begin{aligned} Emissions = & \left(Number\ of\ university\ and\ research\ particle\ accelerators\ in\ the\ country \right) \\ & \bullet \left(SF_6\ Use\ Factor \right) \bullet \left(SF_6\ Charge\ Factor,\ kg \right) \\ & \bullet \left(SF_6\, university\ and\ research\ particle\ accelerator\ Emission\ Factor \right) \end{aligned}$$

Where:

Number of university and research particle accelerators in the country
= The total number of university and research particle accelerators in the country. This

rough method does not require countries to determine the number of accelerators that use SF_6. To determine if a country has a particle accelerator, go to http://www-elsa.physik.uni-bonn.de/Informationen/accelerator_list.html

SF_6 Use Factor = 0.33 Approximately one third of university and research particle accelerators use SF_6 as an insulator.

SF_6 Charge Factor = 2400 kg, SF_6, the average SF_6 charge in a university and research particle accelerator.

SF_6 university and research particle accelerator Emission Factor

= 0.07, the average annual university and research particle accelerator emission rate as a fraction of the total charge.

Tier 2 method – accelerator-level emission-factor approach

If data on the quantity of SF_6 contained within each university and research accelerator are available, a default emission factor of 7 percent may be multiplied by the total SF_6 charge contained in university and research accelerators in the country. The total country SF_6 emission rate from university and research accelerators is therefore calculated from Equation 8.15.

EQUATION 8.15
UNIVERSITY AND RESEARCH PARTICLE ACCELERATOR EMISSIONS (ACCELERATOR-LEVEL EMISSION FACTOR)

$$Total\,Emissions = SF_6\,university\,and\,research\,particle\,accelerator\,Emission\,Factor \bullet \sum Individual\,Accelerator\,Charges$$

Where:

SF_6 university and research particle accelerator Emission Factor

= 0.07, the average annual university and research particle accelerator emission rate as a fraction of the total charge.

Individual User Accelerator Charges

= SF_6 contained within each university and research accelerator.

Tier 3 method –accelerator-level mass-balance method

SF_6 emissions from university and research facilities operating particle accelerators may be most accurately determined at the user level on an accelerator-by-accelerator basis. Emission calculations are estimated by tracking accelerator charge as well as SF_6 consumption and disposal. As detailed in Equation 8.16, the total emissions are equal to the sum of the individual users' emissions. Note, under this method, as the overall SF_6 emission rate from particle accelerators is small compared to other SF_6 uses, the associated SF_6 lost in manufacturing is considered negligible and is not included in the calculation.

EQUATION 8.16
TOTAL RESEARCH ACCELERATOR EMISSIONS

$$Total\ Emissions = \sum Individual\ Accelerator\ Emissions$$

Each particle accelerator's emissions can be calculated as follows:

EQUATION 8.17
RESEARCH ACCELERATOR EMISSIONS (ACCELERATOR-LEVEL MASS-BALANCE)

$$\begin{aligned} Accelerator\ Emissions\ &= \ Decrease\ in\ SF_6\ Inventory\ +\ Acquisitions\ of\ SF_6 \\ &-\ Disbursements\ of\ SF_6 - Net\ Increase\ in\ Accelerator\ Charge \end{aligned}$$

Where:

Decrease in SF_6 Inventory = SF_6 stored in containers at the beginning of the year – SF_6 stored in containers at the end of the year

Acquisitions of SF_6 = SF_6 purchased from chemical producers or distributors in bulk + SF_6 purchased from accelerator manufacturers or distributors with or inside of new accelerator components + SF_6 returned to site after off-site recycling

Disbursements of SF_6 = SF_6 contained in components transferred to other entities + SF_6 returned to suppliers + SF_6 sent off-site for recycling + SF_6 destroyed

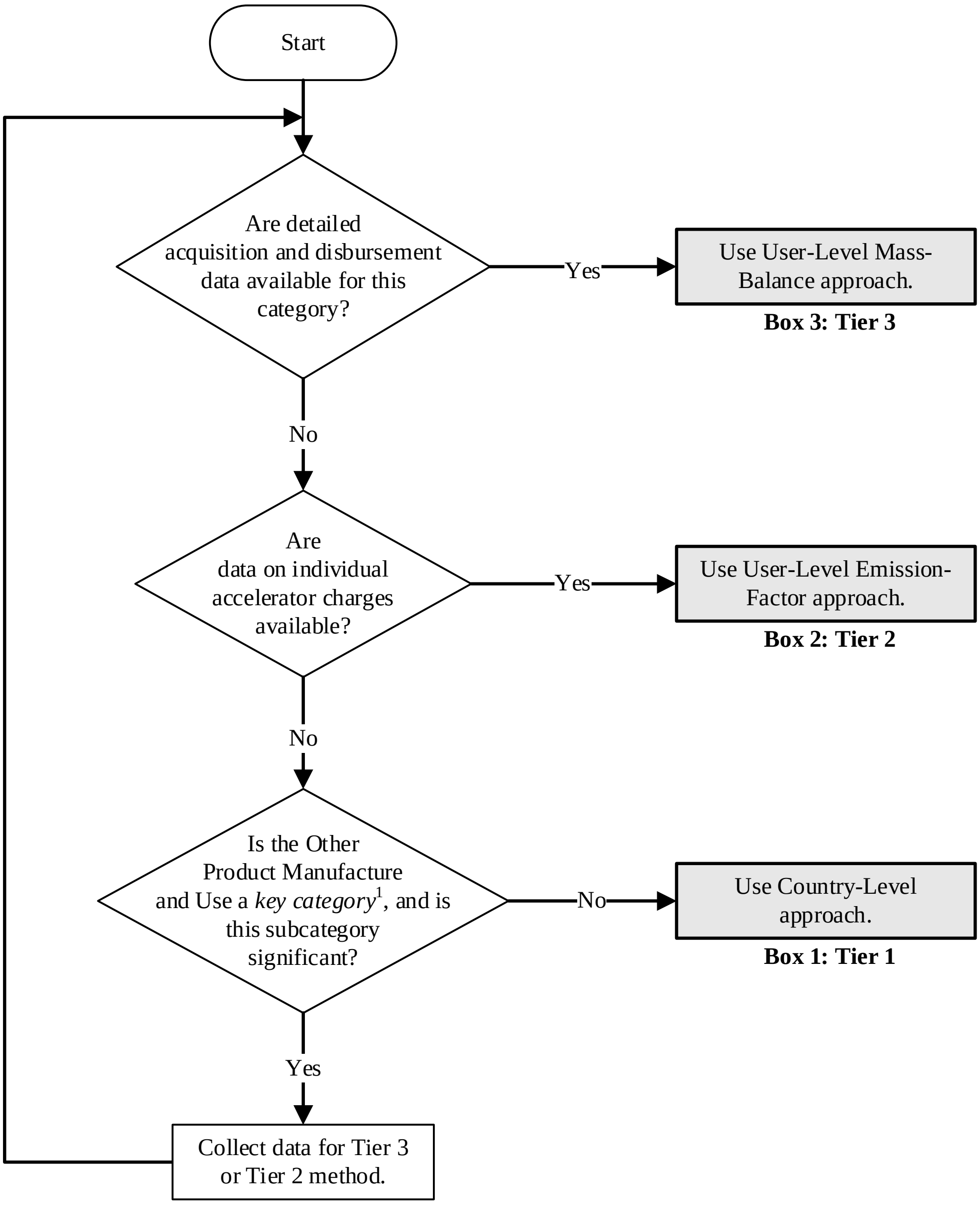
Net Increase in Accelerator Charge = SF_6 Charge of New Components – SF_6 Charge of Retiring Components

SF_6 EMISSIONS FROM INDUSTRIAL AND MEDICAL PARTICLE ACCELERATORS

SF_6 is used as an insulating gas in two types of industrial particle accelerators (low and high voltage) and also in medical (cancer therapy) particle accelerators, as is the case for university and research particle accelerators. However, the emission and charge factors for industrial and medical particle accelerators are different from those of university and research accelerators, as discussed below.

Global banked capacity for industrial particle accelerators is roughly estimated to be 500 tonnes with annual SF_6 emissions of 35 tonnes. Global banked capacity for medical (radiotherapy) particle accelerators is roughly estimated to be less than 5 tonnes with annual SF_6 emissions of less than 5 tonnes. (Schwarz, 2005).

Figure 8.4 Decision tree for industrial and medical particle accelerators



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.

Tier 1 method – country-level method

In cases where individual user accelerator charge data is unavailable, one extremely rough method involves determining the total number of particle accelerators by process description in the country and using factors to determine the country level annual emission rate as noted in Equation 8.18. For this Tier 1 method, the only data that requires collection is the total number of particle accelerators which contain SF_6 by process description in the given country.

EQUATION 8.18

INDUSTRIAL/MEDICAL ACCELERATOR EMISSIONS (COUNTRY-LEVEL)

$$\begin{aligned} Emissions &= Number\ of\ particle\ accelerators\ that\ use\ SF_6\ by\ process\ description\ in\ the\ country \\ &\bullet SF_6\ Charge\ Factor,\ kg \bullet SF_6\ applicable\ particle\ accelerator\ Emission\ Factor \end{aligned}$$

Where:

Number of particle accelerators by type in the country

= The total number of particle accelerators by type (industrial high voltage, industrial low voltage and radiotherapy) that use SF_6 in the country, 1, 2, etc. (Only count particle accelerators that use SF_6. This differs for the Tier 1 calculation for university and research particle accelerators)

SF_6 Charge Factor = The average SF_6 charge in a particle accelerator by process description as noted below.

SF_6 particle accelerator Emission Factor

= The average annual SF_6 particle accelerator emission rate as a fraction of the total charge by process description.

TABLE 8.9
AVERAGE SF_6 CHARGE IN A PARTICLE ACCELERATOR BY PROCESS DESCRIPTION

Process Description	SF_6 Charge Factor, kg
Industrial Particle Accelerators – high voltage (0.3-23 MV)	1300
Industrial Particle Accelerators –low voltage (<0.3 MV)	115
Medical (Radiotherapy)	0.5[a]

[a] This is the average of values ranging from 0.05 kg to over 0.8 kg, depending on model and manufacturer.

Source: Schwarz (2005)

Tier 2 method – user-level emission-factor approach

If data on the quantity of SF_6 contained within each industry and medical accelerator are available, use the Tier 2 method for university and research facilities; however, multiply the emission factor for each process description provided below by the total, country-specific SF_6 charge for that process description.

TABLE 8.10
EMISSION FACTOR FOR EACH PROCESS DESCRIPTION,
(SF_6 EMISSIONS FROM INDUSTRIAL AND MEDICAL PARTICLE ACCELERATORS)

Process Description	Emission Factor, kg /kg SF_6 charge
Industrial Particle Accelerators – high voltage (0.3-23 MV)	0.07
Industrial Particle Accelerators – low voltage (<0.3 MV)	0.013
Medical (Radiotherapy)	2.0[a]

[a] This emission factor is the average of values ranging from 1 kg to 10 kg per kg charge, depending on model, manufacturer, and service intervals.

Source: Schwarz (2005)

Tier 3 method – user-level mass-balance method

To calculate SF_6 emissions from industrial and medical particle accelerators, use the same Tier 3 method as the university and research facilities. The customer service organisations for manufacturers and distributors of the equipment are likely to have information on equipment stocks, imports, and exports, and on the quantities of SF_6 used to fill and refill the equipment.

EMISSIONS FROM OTHER APPLICATIONS OF SF_6 AND PFCs

It is *good practice to* contact all gas producers/distributors to identify SF_6 and PFC users and to investigate the gas consumption of source categories other than those mentioned above. The key difference among the applications discussed below is the typical delay between the purchase of the SF_6 or PFC and the release of the chemical. In some cases (e.g., SF_6 used in sound-proof glazing, PFCs used as heat transfer fluids), the chemical is fairly well contained during the life of the equipment or product, and most emissions are associated with the manufacture and disposal of the product. In these cases, the delay between the purchase of the chemical and its final emission depends on the lifetime of the product, ranging from three years for tyres and sport-shoes to 25 years for sound-proof glazing. In other cases (e.g., use of SF_6 and PFCs as tracers or in medical applications), the chemical is fully emitted within a year of its purchase. If, as a result of an initial survey, applications with distinctive delayed emissions appear significant, then *good practice* is to use a source category-specific emission calculation, taking into account the delay in emissions.

Adiabatic uses

Adiabatic uses of SF_6 and some PFCs exploit the low permeability of these gases through rubber. Historically, SF_6 has been the dominant gas in these applications; however, PFCs with similar molecular weights (such as C_3F_8) have recently been used as well. Applications with a delay period of 3 years include or car tyres, sport shoe soles and tennis balls (Schwarz *et al.*, 1996). For applications with emissions that are delayed by three years, the following formula can be used.

EQUATION 8.19

ADIABATIC PROPERTY APPLICATIONS

$$Emissions\ in\ year\ t\ =\ Sales\ in\ year\,(t\ -3)$$

Sound-proof glazing

Double-glazed sound-proof windows: Approximately one-third of the total amount of SF_6 purchased is released during assembly (i.e., filling of the double glass window) (Schwarz/Leisewitz, 1999). For the stock of gas remaining inside the window (capacity), an annual leakage rate of 1 percent is assumed (including glass breakage). Thus, about 75 percent of initial stock remains at the end of its 25-year lifetime. The application of SF_6 in windows began in 1975, so disposal is only beginning to occur. Emissions from this source sub-category should be calculated using Equations 8.20 to 8.22:

EQUATION 8.20

DOUBLE-GLAZED WINDOWS: ASSEMBLY

$$Assembly\ Emissions in\ year\ t = 0.33 \bullet SF_6\ purchased\ to\ fill\ windows\ assembled\ in\ year\ t$$

EQUATION 8.21

DOUBLE-GLAZED WINDOWS: USE

$$Leakage\ Emissions\ in\ year\ t\ =\ 0.01 \bullet Capacity\ of\ Existing\ Windows\ in\ year\ t$$

EQUATION 8.22

DOUBLE-GLAZED WINDOWS: DISPOSAL

$$Disposal\ Emissions in\ year\ t = Amount\ Left\ in\ Window\ at\ End\ of\ Lifetime in\ year\ t \bullet (1\ - Recovery\ Factor)$$

Unless country-specific data are available, a default recovery factor value of zero should be assumed in Equation 8.22. If no specific information is available for these sub-source categories, *good practice* is to treat them as prompt emissions.

Fluorinated compounds used to waterproof electronic circuits

There are two basic processes to adding waterproofing layers onto assembled electronic circuits:

1. Liquid-based PFOS or PFOA-containing films, applied by aerosol spray or immersion, or
2. Long-chain perfluorocarbon polymers applied by gas-phase reaction in a plasma.

The second process can result in emissions of fluorinated compounds (FCs) and is therefore the focus of this guidance. The plasma deposition process involves the introduction of a variety of hydrocarbon gases where the hydrogen atoms are replaced by fluorine supplied from an FC gas source that is decomposed in the plasma. Periodically, the process chamber is also cleaned using FC gases in a way similar to the way that TFD chambers are cleaned in the semiconductor industry. (See the *2006 IPCC Guidelines*, Volume 3, Chapter 6 and the *2019 Refinement*, Volume 3, Chapter 6.)

Table 8.11 below provides default emission factors, expressed in grams of gas per circuit board, for the three FCs understood to account for the vast majority of GWP-weighted emissions from this process. Inventory compilers should apply all three emission factors to the number of circuit boards waterproofed to obtain a complete estimate of emissions from this source category.

TABLE 8.11 (NEW)
EMISSION FACTOR FOR WATERPROOFING OF ELECTRONIC CIRCUITS

Gas Emitted	Emissions (g)/Circuit Board
CF_4	0.006
C_2F_6	0.004
CHF_3	0.003

Note:

Figures are expert judgement conducted by authors of Chapter 8 based on confidential data from Edwards Vacuum Ltd., 2017.

The emissions used to develop these emission factors were measured by FTIR on a working facility installation, and were originally expressed in terms of gCO_2/week/chamber. The numbers above were calculated based on the assumption that each process chamber processes 60,000 circuit boards per week. The emissions included both higher-GWP gases (CF_4, C_2F_6 and CHF_3) and lower-GWP gases (CH_4, C_3F_6, COF_2, C_2H_4), but emission factors are provided only for higher-GWP gases as their emissions are dominant (8,453,881 vs. 830 gCO2eq/week/chamber). Because the actual proportions of the emitted gases are sensitive process information for the company that provided the data, the GWP-weighted emissions were divided equally among the three emitted gases on a gCO2eq basis, and were then converted into grams of gas, to obtain the emission factors in Table 8.11.

EQUATION 8.22A (NEW)
WATERPROOFING OF ELECTRONIC CIRCUITS

$$Emissions_i = EF_i \bullet n$$

Where:

$Emissions_i$ = Emissions of each gas i listed in Table 8.11

n = Number of circuit boards manufactured

EF_i = Emission factor for gas i in Table 8.11

Textile, carpet, leather and paper fluorinated treatment emissions

Fluorine-based treatment processes are used to control the surface properties of textile, carpet, leather, or paper fibres, and – inter alia – to enhance their hydrophobicity, to increase their stain resistance, dyeing ability, or mechanical strength, and to produce wrinkle-free materials (Lacasse & Baumann 2004; Schindler & Hauser 2004; Singha 2012; Gulrajani 2013; Roshan 2014). The main treatment technologies currently in use are based on wet processes, including the pad-dry-cure method among others (Roshan 2014; Heydebreck et al. 2016; Goswami 2017; Williams 2018). Another emerging technology is based on plasma processes used to treat, etch, or deposit polymers on the surface of the substrate (Morent et al. 2008; Jafari et al. 2013; Zille et al. 2015; Gotoh et al. 2017).

Although several international and national reports refer to the possible off-gas emissions of fluorinated compounds (FC) into the atmosphere during wet and plasma treatments of textile, carpet, leather, and paper, no representative emission factors appear to be available to estimate greenhouse gas (GHG) emissions from such processes (EPA 1997; Schönberger & Schäfer 2003; MoEU 2012; DEPA 2013; UNIDO et al. 2017). It is probable that FCs emissions of wet-based processes mainly occur during the pad-dry-cure process or other thermal coating processes, but the amount of unreacted input chemicals that may be emitted through evaporative losses or the type and amount of by-products formed during these processes as well as their relevance as GHG gases do not appear to have been thoroughly characterized (IPPC 2003; OECD 2004). The extent to which plasma-based textile treatment processes have penetrated volume production is unclear, but, by analogy with plasma-based processes used in the electronics industry, and considering that many FC molecules are particularly stable and difficult to disassociate, the utilization efficiency of the input gas is likely to be limited, and FC emissions resulting from the incomplete use of input gases such asCF_4, C_2F_6, CHF_3, SF_6, and other fluorine-containing molecules in plasma processes may be significant. Since the authors were not able, at the time of publication of the *2019 Refinement*, to estimate the volume of fluorinated compounds that are used or emitted by the textile, carpet, leather, and paper industries, FC emissions in this sector could represent a significant new source, due to the large volume of substrates treated and the sheer size and global nature of the industry (KEMI 2014).

While it does not appear feasible at the time of publication of the *2019 Refinement* to apply a reporting methodology for this new source category based on default emissions factors (e.g. based on representative emission factors to estimate emissions of GHGs per mass or per surface area of substrate treated), a three-tiered methodological framework (Tier 1, Tier 2a, Tier 2b) to report emissions once default emission factors become available is proposed. In addition, a Tier 3 method that can readily be applied, based on measured emission factors is also provided. Countries seeking to report FC emissions from textile, carpet, leather and paper industries should work with equipment manufacturers and users of such equipment to measure equipment-specific, process-specific, or site-specific emission factors, with the aim of developing representative default emission factors that could be used for site-specific, domestic, or industry-wide inventories.[2] The proposed Tier 1, Tier 2a, Tier 2b, and Tier 3 methods are described in Appendix 1. Possible Approaches for Estimating FC Emissions from Textile, Carpet, Leather and Paper Industries: Basis for Future Methodological Development, and preliminary guidance about how to measure emissions factors and develop defaults is also provided.

PFCs used as heat transfer fluids in consumer and commercial applications

PFCs are used as heat transfer fluids in a number of high-power-density commercial and consumer electronic applications. Commercial applications include cooling for supercomputer, telecommunication, and airport radar systems, as well as drive units (rectifiers) on high-speed trains (Burton, 2006). These applications consume much smaller volumes of liquid PFCs than electronics manufacturing, but are believed to be significant among ‘niche’ applications. Consumer applications include cooling kits for desktop computers that are operated at high voltages to increase their processing speed. The specific PFCs used in these applications are believed to be similar to those identified as heat transfer fluids in electronics manufacturing in Chapter 6. In all of these applications, the liquid PFCs are used in closed modules, indicating that most emissions occur during the manufacture, maintenance, and disposal of the product or equipment. Thus, if inventory compilers can acquire information on emission rates during the manufacture, maintenance, and disposal of the equipment, along with the quantities of equipment manufactured, used, and disposed each year, they can use the Tier 2 or Tier 3 method for electrical equipment to estimate emissions. For applications with different emissions profiles (e.g., prompt emissions), the appropriate equation from Section 8.2 may be used.

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[2] For the explanation about the role of Appendices please refer to the Overview Chapter

PFCs used in cosmetic and medical applications

PFCs with relatively large molecular weights (e.g., $C_{10}F_{18}$) are used in cosmetic and medical applications, exploiting their ability to carry oxygen to living tissue (May, 2006). Cosmetic applications include anti-wrinkle creams and are estimated to consume fairly small amounts. Current and potential medical applications include storage of pancreatic tissue for transplants (using the 'two-layer method'), eye surgery (to repair retinal tears), pneumonectomy (lung therapy and diagnosis), use as a contrast agent in ultrasonic and MRI examinations, blood extension, wound healing, and treatment of diseases of the middle ear. All but the first two medical applications involve only small quantities and/or are at the research stage. Storage of pancreatic tissue is a small but growing application. Emissions from medical uses are uncertain but are believed to be small.

In all of these applications, the PFC is believed to be emitted into the atmosphere within one year of its purchase. Thus, emissions from these sources can be estimated using Equation 8.23 for prompt emissions.

Any other uses of SF_6 and PFCs

Other applications for SF_6 and PFCs that are not specifically addressed above include their use as tracers (in leak detection, indoor and outdoor tracking of air-masses, and oil recovery[3]) and use of SF_6 in the production of optical cables (for fluorodoping of glass fibres[4]). Often the gases or liquids are emitted within one year of purchase. In this case, *good practice* in calculating SF_6 and PFC emissions from these 'prompt' emissive applications is to use the following formula**:**

EQUATION 8.23
PROMPT EMISSIONS

$$Emissions\ in\ year\ t\ =\ (0.5 \bullet Amount\ Sold\ in\ year\ t) + (0.5 \bullet Amount\ Sold\ in\ year\ t\ -1)$$

This equation is similar to the equation for prompt ozone depleting substances (ODS) Substitute applications (e.g., aerosols and solvents) addressed in Chapter 7 of this volume. The equation covers more than one year because both sales and emissions are assumed to be continuous over the year; that is, chemical sold in the middle of year t-1 is not fully emitted until the middle of year t.

8.3.2.2 CHOICE OF EMISSION FACTORS

For 'other' source categories of SF_6 and PFCs that contribute substantially to a country's SF_6 and PFCs emissions, countries are encouraged to develop country-specific emission factors based on occasional surveys of representative subsets of sources. It is *good practice* to clearly document such emission factors. Default emission factors are provided above for AWACS, accelerators, waterproofing of electronic circuits, prompt emissive applications and adiabatic applications, including windows.

8.3.2.3 CHOICE OF ACTIVITY DATA

No refinement.

8.3.2.4 COMPLETENESS

No refinement.

8.3.2.5 DEVELOPING A CONSISTENT TIME SERIES

No refinement.

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[3] D. Vlachogiannis *et al*. (2005). This paper indicated that some fraction of injected PFCs and SF_6 was destroyed during fuel combustion, but the magnitude of this fraction (compared to the fraction of injected chemical that escaped before combustion) was unclear.

[4] See further information on this application in Schwarz (2005).

8.3.3 Uncertainty assessment

No refinement.

8.3.4 Quality assurance / quality control (QA/QC), reporting and documentation

No refinement.

8.4 N_2O FROM PRODUCT USES

No refinement.

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SECTIONS 8.1 - 8.3

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ANNEX 1

WORKSHEETS

Contents

Annex 1 Worksheets

In this Annex only new and updated worksheets are presented (Annex 1 Volume 3 of the *2019 Refinement)*. The worksheets for categories 2B9, 2C1, 2C3, 2E and 2G2 of this annex should be used instead of the worksheets of categories 2B9, 2C1, 2C3, 2E and 2G2 in Annex 1 Volume 3 of the *2006 IPCC Guidelines*. The worksheets for categories 2B10 and 2C7 are new ones and should be used together with other worksheets in Annex 1 Volume 3 of the *2006 IPCC Guidelines*.

The other worksheets of Annex 1 of Volume 3 of the *2006 IPCC Guidelines* are not refined.

2B9 FLUOROCHEMICAL PRODUCTION (UPDATED)

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**		
Category	**Chemical Industry - Fluorochemical Production**		
Category Code	**2B9**		
Sheet	**1 of 2 HFC-23 Emissions from HCFC-22 Production**		
A	B	C	D
Amount of HCFC-22 Produced	Emission Factor	HFC-23 Emissions	HFC-23 Emissions
(kg)	(kg HFC-23/kg HCFC-22 produced)	(kg)	(Gg)
		C = A * B	D = $C/10^6$

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**				
Category	**Chemical Industry - Fluorochemical Production**				
Category Code	**2B9**				
Sheet	**2 of 2 Emissions from Production of Fluorochemicals (other than HFC-23 emissions from HCFC-22 production)**				
		A	B	C	D
Principal Fluorochemical Produced 1)	Fluorochemical Emitted (may be compound produced, reactant, intermediate, or by-product) 1)	Amount of Principal Fluorochemical Produced (or Other Process Activity)	Fluorochemical Product, Reactant, Intermediate, or Byproduct Emission Factor 2)	Emissions	Emissions
		(kg)	(kg fluorinated GHG emitted/kg fluorochemical produced)	(kg)	(Gg)
				C = A * B	D = $C/10^6$

1) Insert additional rows if necessary.

2) See Table 3.28a for Tier 1 default emission factors. The default emission factor includes process vents, equipment leak, and cylinder venting emissions

(Worksheet 3 of 3 from the *2006 IPCC Guidelines* - Removed)

2B10 HYDROGEN PRODUCTION (NEW)

(New Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Chemical Industry - Hydrogen Production**			
Category Code	**2B10**			
Sheet	**1 of 3 CO_2 Emissions from Hydrogen Production (calculation based on feedstock used)**			
	A	B	C	D
Type of Feedstock	Feedstock Consumption	Carbon Content Factor	CO_2 recovered	CO_2 Emissions
	(GJ)	(tonne C / GJ feedstock)	(tonne CO_2)	(Gg)
				D = (A * B * (44/12) – C)/1000
Total				
Note: Inventory compilers should use either this sheet (1 of 3), the second sheet (2 of 3) or the third sheet (3 of 3), not all of them. This sheet is for the Tier 1a method.				

(New Worksheet)

Sector	**Industrial Processes and Product Use**				
Category	**Chemical Industry - Hydrogen Production**				
Category Code	**2B10**				
Sheet	**2 of 3 CO_2 Emissions from Hydrogen Production (calculation based on hydrogen produced)**				
	A	B	C	D	E
Type of Feedstock	Hydrogen Produced	Feedstock Requirement Factor	Carbon Content Factor	CO_2 recovered	CO_2 Emissions
	(tonne)	(GJ feedstock / tonne hydrogen produced)	(tonne C / GJ feedstock)	(tonne CO_2)	(Gg)
					E = (A * B * C * (44/12) – D)/1000
Total					
Note: Inventory compilers should use either this sheet (2 of 3), the first sheet (1 of 3) or the third sheet (3 of 3), not all of them. This sheet is for the Tier 1b method.					

(New Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Chemical Industry - Hydrogen Production**
Category Code	**2B10**
Sheet	**3 of 3 CO_2 Emissions from Hydrogen Production (calculation based on hydrogen produced)**

A	B	C	D
Hydrogen Produced	Feedstock Requirement Factor	Carbon Content Factor	CO_2 Emissions
(tonne)	(GJ feedstock / tonne hydrogen produced)	(tonne C / GJ feedstock)	(Gg)
			D = (A * B * C * (44/12))/1000

Note: Inventory compilers should use either this sheet (3 of 3), the first sheet (1 of 3) or the second sheet (2 of 3), not all of them. This sheet is for the Tier 1c method.

2C1 IRON AND STEEL PRODUCTION (UPDATED)

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Metal Industry - Iron and Steel Production**			
Category Code	**2C1**			
Sheet	**1 of 3 CO_2 Emissions**			
Type of Steelmaking Method, etc	A	B	C	D
	Amount of Steel or Iron Production	Emission Factor	CO_2 Emissions	CO_2 Emissions
	(tonne crude steel produced, pig iron, DRI, sinter or pellet)	(tonne CO_2/tonne production)	(tonne CO_2)	(Gg CO_2)
			C = A * B	$D = C/10^3$
Basic Oxygen Furnace				
Electric Arc Furnace				
Open Hearth Furnace				
Pig Iron Production (not converted into steel)				
Direct Reduced Iron (DRI) Production				
Sinter Production				
Pellet Production				
Blast Furnace Gas (BFG) and Converter Gas (LDG) from flaring				
TOTAL				

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Metal Industry - Iron and Steel Production**			
Category Code	**2C1**			
Sheet	**2 of 3 CH_4 Emissions**			
Type of Production	A	B	C	D
	Amount of Production	Emission Factor	CH_4 Emissions	CH_4 Emissions
	(tonne sinter, DRI or pig iron)	(kg CH_4/tonne production)	(kg)	(Gg)
			C = A * B	$D = C/10^6$
Sinter Production				
Direct Reduced Iron (DRI) Production				
Pig Iron Production				
TOTAL				

(New Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Metal Industry - Iron and Steel Production**
Category Code	**2C1**
Sheet	**3 of 3 N_2O Emissions**

Type of Production	A	B	C	D
	Amount of Production	Emission Factor	N_2O Emissions	N_2O Emissions
	(tonne BFG and LDG)	(tonne N_2O/tonne production)	(tonne)	(Gg)
			C = A * B	D = C/10^3
Blast Furnace Gas (BFG) and Converter Gas (LDG) from flaring				
TOTAL				

2C3 ALUMINIUM PRODUCTION (UPDATED)

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Metal Industry - Aluminium Production**			
Category Code	**2C3**			
Sheet	**1 of 14: CO_2 Emissions From Anode or Paste Consumption**			
Type of Technology	A	B	C	D
	Amount of Aluminium Production	Emission Factor	CO_2 Emissions	CO_2 Emissions
	(tonne aluminium produced)	(tonne CO_2/tonne aluminium produced)	(tonne)	(Gg)
			$C = A * B$	$D = C/10^3$
Prebake				
Soderberg				
Total				

(New Worksheet)

Sector	**Industrial Processes and Product Use**				
Category	**Metal Industry - Aluminium Production**				
Category Code	**2C3**				
Sheet	**2 of 14: CO_2 Emissions From Sintering**[1)]				
Type of Technology	A	B	C	D	E
	Mass of Alumina Produced	Mass Fraction of Alumina Produced by Sintering Process	Emission Factor for Sintering	CO_2 Emissions	CO_2 Emissions
	(tonne)	(fraction)	(tonne CO_2/ tonne alumina)	(tonne CO_2)	(Gg CO_2)
				$D = A * B * C$	$E = D/10^3$
Bayer-sintering					
Nepheline-sintering process					
Total					

1) CO_2 emissions from Sintering are estimated here only for alumina production via alternative Bayer-sintering and Nepheline-sintering processes. CO_2 emissions from the conventional Bayer process are already accounted for in existing guidance for lime production (Volume 3, sub-chapter 2.3) and fossil fuel combustion (Volume 3, Chapter 2)

(New Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Metal Industry - Aluminium Production**
Category Code	**2C3**
Sheet	**3 of 14: CO_2 Emissions From Lime Production[1)]**

Type of Lime Produced[2), 3)]	A	B	C	D
	Mass of Lime Produced	Emission Factor for Lime Production	CO_2 Emissions	CO_2 Emissions
	(tonne)	(tonne CO_2/ tonne lime)	(tonne CO_2)	(Gg CO_2)
			$C = A * B$	$D = C/10^3$
Total				

1) CO_2 emissions from Lime Production are estimated here, only if lime production is a part of the alumina production process *and* is not already accounted for separately as emissions from the Mineral Industry, under the Lime Production category.

2) Insert additional rows if more than two types of lime are produced.

3) When country-specific information on lime production by type is not available, apply the default emission factor to national level lime production data (see Equation 2.8 in sub-chapter 2.3, Chapter 2, Volume 3).

(New Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Metal Industry - Aluminium Production**
Category Code	**2C3**
Sheet	**4 of 14: CO_2 Emissions (Total)**

	A	B	C	D
	Emissions from Anode or Paste Consumption	Emissions from Sintering[1]	Emissions from Lime Production[2]	Total CO_2 Emissions
	(Gg)	(Gg)	(Gg)	(Gg)
	From D in Sheet 1 of 14	From E in Sheet 2 of 14	From D in Sheet 3 of 14	$D = A + B + C$
Total				

1) CO_2 emissions from Sintering are estimated here only for alumina production via alternative Bayer-sintering and Nepheline-sintering processes.

2) CO_2 emissions from Lime Production are estimated here, only if lime production is a part of the alumina production process *and* is not already accounted for separately as emissions from the Mineral Industry, under the Lime Production category.

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Metal Industry - Aluminium Production**			
Category Code	**2C3**			
Sheet	**5 of 14: CF_4 Emissions (High Voltage Anode Effect)**			
Type of Technology 1) , 2) (please specify)	A	B	C	D
	Amount of Aluminium Production	Emission Factor	HVAE-CF_4 Emissions	HVAE-CF_4 Emissions
	(tonne aluminium produced)	(kg CF_4/tonne aluminium produced)	(kg)	(Gg)
			C = A * B	D = $C/10^6$
Total				

1) Insert relevant type of technology, e.g.: PFPB $_L$, PFPB $_M$, PFPB $_{MW}$, SWPB, VSS, HSS. For more details, refer to Section 4.4.1 in Volume 3, Chapter 4.

2) Insert additional rows if necessary.

(New Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Metal Industry - Aluminium Production**			
Category Code	**2C3**			
Sheet	**6 of 14: CF_4 Emissions (Low Voltage Anode Effect)**			
Type of Technology 1) , 2) (please specify)	A	B	C	D
	Amount of Aluminium Production	Emission Factor	LVAE-CF_4 Emissions	LVAE-CF_4 Emissions
	(tonne aluminium produced)	(kg CF_4/tonne aluminium produced)	(kg)	(Gg)
			C = A * B	D = $C/10^6$
Total				

1) Insert relevant type of technology, e.g.: PFPB $_L$, PFPB $_M$, PFPB $_{MW}$, SWPB, VSS, HSS. For more details, refer to Section 4.4.1 in Volume 3, Chapter 4.

2) Insert additional rows if necessary.

(New Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Metal Industry - Aluminium Production**
Category Code	**2C3**
Sheet	**7 of 14: CF_4 Emissions (Cell Start-Up)[1)]**

Type of Technology[2), 3)] (please specify)	A	B	C	D
	No. of Cell Start-Ups	CSU Emission Factor	CSU-CF_4 Emissions	CSU-CF_4 Emissions
	(cell start-ups)	(kg CF_4 / cell-start up)	(kg)	(Gg)
			C = A * B	D = C/10^6
Total				

1) Cell start-up (CSU) emissions are estimated, only if they are not already accounted for with HVAE and LVAE emissions. The worksheet here relates to the Tier 3 method of accounting CSU emissions; there are no Tier 1 default values are available for CSU emissions. For more details, refer to Section 4.4.2.3 in Volume 3, Chapter 4.

2) Insert relevant type of technology, e.g.: PFPB $_L$, PFPB $_M$, PFPB $_{MW}$, SWPB, VSS, HSS. For more details, refer to Section 4.4.1 in Volume 3, Chapter 4.

3) Insert additional rows if necessary.

(New Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Metal Industry - Aluminium Production**
Category Code	**2C3**
Sheet	**8 of 14: CF_4 Emissions (Total)**

	A	B	C	D
	HVAE-CF_4 Emissions	LVAE-CF_4 Emissions	CSU-CF_4 Emissions[1)]	Total CF_4 Emissions
	(Gg)	(Gg)	(Gg)	(Gg)
	From D in Sheet 5 of 14 [2)]	From D in Sheet 6 of 14	From D in Sheet 7 of 14	D = A + B + C
Total				

1) Cell start-up (CSU) emissions are estimated, only if they are not already accounted for with HVAE and LVAE emissions. For more details, refer to Section 4.4.2.3 in Volume 3, Chapter 4.

2) Alternatively, if Tier 2b method is used, total HVAE-CF_4 emissions can be sourced from either: (a) from E in Sheet 12 of 14, or (b) from E in Sheet 13 of 14.

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Metal Industry - Aluminium Production**			
Category Code	**2C3**			
Sheet	**9 of 14: C_2F_6 Emissions (High Voltage Anode Effect)**			
Type of Technology1) , 2) (please specify)	A	B	C	D
	Amount of Aluminium Production	Emission Factor	HVAE-C_2F_6 Emissions	HVAE-C_2F_6 Emissions
	(tonne aluminium produced)	(kg C_2F_6/tonne aluminium produced)	(kg)	(Gg)
			C = A * B	D = C/10^6
Total				

1) Insert relevant type of technology, e.g.: PFPB $_L$, PFPB $_M$, PFPB $_{MW}$, SWPB, VSS, HSS. For more details, refer to Section 4.4.1 in Volume 3, Chapter 4.

2) Insert additional rows if necessary.

(New Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Metal Industry - Aluminium Production**			
Category Code	**2C3**			
Sheet	**10 of 14: C_2F_6 Emissions (Cell Start-Up)1)**			
Type of Technology2) , 3) (please specify)	A	B	C	D
	No. of Cell Start-Ups	CSU Emission Factor	CSU-C_2F_6 Emissions	CSU-C_2F_6 Emissions
	(cell start-ups)	(kg C_2F_6 / cell-start up)	(kg)	(Gg)
			C = A * B	D = C/10^6
Total				

1) Cell start-up (CSU) emissions are estimated, only if they are not already accounted for with HVAE and LVAE emissions. The worksheet here relates to the Tier 3 method of accounting CSU emissions; there are no Tier 1 default values are available for CSU emissions. For more details, refer to Section 4.4.2.3 in Volume 3, Chapter 4.

2) Insert relevant type of technology, e.g.: PFPB $_L$, PFPB $_M$, PFPB $_{MW}$, SWPB, VSS, HSS. For more details, refer to Section 4.4.1 in Volume 3, Chapter 4.

3) Insert additional rows if necessary.

(New Worksheet)

Sector	**Industrial Processes and Product Use**		
Category	**Metal Industry - Aluminium Production**		
Category Code	**2C3**		
Sheet	**11 of 14: C_2F_6 Emissions (Total)**		
	A	B	C
	HVAE-C_2F_6 Emissions	CSU-C_2F_6 Emissions	Total C_2F_6 Emissions
	(Gg)	(Gg)	(Gg)
	From D in Sheet 9 of 14 [1)]	From D in Sheet 10 of 14	C = A + B
Total			

1) Alternatively, if Tier 2b method is used, total HVAE-C_2F_6 emissions can be sourced from either: (a) from G in Sheet 12 of 14, or (b) from E in Sheet 14 of 14.

The following worksheets are included to provide extra clarity on the use of new Tier 2b methods for estimating CF_4 and C_2F_6 emissions from HVAEs (using the duration of individual HVAEs) – these can be used in place of Sheets 5 of 14 for HVAE-CF_4 and Sheet 9 of 14 for HVAE-C_2F_6. For more details refer to section 4.4.2.3 in Volume 3, Chapter 4:

- Sheet 12 of 14 is for estimating CF_4 and C_2F_6 using the Tier 2b method – Marks and Nunez approach.
- Sheets 13 and 14 of 14 are for estimating CF_4 and C_2F_6, respectively, using the Tier 2b method – Dion *et al.* approach.

(New Worksheet)

Sector	**Industrial Processes and Product Use**					
Category	**Metal Industry - Aluminium Production**					
Category Code	**2C3**					
Sheet	**12 of 14: CF_4 and C_2F_6 Emissions (High Voltage Anode Effect) Based on Individual HVAE Durations (Tier 2b – Marks & Nunez approach)[1)]**					
A	B	C	D	E	F	G
Individual HVAE Duration[2)]	Average Line Current during Individual HVAE	K_1 Emission Rate Coefficient for CF_4 [3)]	K_2 Emission Rate Coefficient for CF_4 [3)]	HVAE-CF_4 Emissions	Weight fraction C_2F_6 / CF_4 ratio	HVAE-C_2F_6 Emissions
(seconds)	(kA)	(dimension-less)	(dimension-less)	(Gg)	(kg C_2F_6 / kg CF_4)	(Gg)
				$E = ((C*A^D)*B)/10^9$		G = E * F
Total						

1) This Tier 2b method estimates CF_4 and C_2F_6 emissions for individual HVAEs. Total HVAE-CF_4 and total HVAE-C_2F_6 emissions are the sum of respective emissions for all individual HVAEs.

2) Insert additional rows for every new HVAE.

3) For K_1 and K_2 emission rate coefficients, refer to Table 4.16a in Volume 3, Chapter 4, section 4.4.2.4.

(New Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Metal Industry - Aluminium Production**
Category Code	**2C3**
Sheet	**13 of 14: CF_4 Emissions (High Voltage Anode Effect) Based on Individual HVAE Durations (Tier 2b – Dion *et al.* approach)1)**

A	B	C	D	E
Individual HVAE Duration2)	Average Daily Metal Production per Cell	C_1 Emission Rate Coefficient for CF_4	C_2 Emission Rate Coefficient for CF_4	HVAE-CF_4 Emissions
(seconds)	(tonnes aluminium / day)	(g CF_4 / s. tonne aluminium)	(dimensionless)	(Gg)
		0.6415 * B + 5.878	-0.0972* B + 0.8905	$E = ((C * A^D)* B) / 10^9$
Total				

1) This Tier 2b method estimates CF_4 emissions for individual HVAEs. Total HVAE-CF_4 emissions is the sum of emissions for all individual HVAEs.

2) Insert additional rows for every new HVAE.

(New Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Metal Industry - Aluminium Production**
Category Code	**2C3**
Sheet	**14 of 14: C_2F_6 Emissions (High Voltage Anode Effect) Based on Individual HVAE Durations (Tier 2b – Dion *et al.* approach)1)**

A	B	C	D	E
Individual HVAE Duration2)	Average Daily Metal Production per Cell	C_3 Emission Rate Coefficient for C_2F_6	C_4 Emission Rate Coefficient for C_2F_6	HVAE-C_2F_6 Emissions
(seconds)	(tonnes aluminium / day)	(g C_2F_6 /s. tonne aluminium)	(dimensionless)	(Gg)
		$0.238 * B^2 - 1.407 * B + 2.342$	$-0.0981 * B^2 + 0.381 * B + 0.3413$	$E = ((C * A^D)* B) / 10^9$
Total				

1) This Tier 2b method estimates CF_4 emissions for individual HVAEs. Total HVAE-CF_4 emissions is the sum of emissions for all individual HVAEs.

2) Insert additional rows for every new HVAE.

2C7 RARE EARTH PRODUCTION (NEW)

(New Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Metal Industry – Rare Earths Production**			
Category Code	**2C7**			
Sheet	**1 of 4: CO_2 Emissions**			
Type of Rare Earth Metal / Alloy 1), 2) (please specify)	A	B	C	D
	Amount of Rare Earth Production	Emission Factor	CO_2 Emissions	CO_2 Emissions
	(tonne rare earth metal produced)	(tonne CO_2/tonne metal produced)	(tonne)	(Gg)
			$C = A * B$	$D = C/10^3$
Total				

1) Insert relevant rare earth metal or alloy, e.g.: Nd metal, Pr metal, Dy-Fe alloy, etc. For more details, refer to Section 4.8.1 in Volume 3, Chapter 4.

2) Insert additional rows if necessary.

(New Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Metal Industry - Rare Earths Production**			
Category Code	**2C7**			
Sheet	**2 of 4: CF_4 Emissions**			
Type of Rare Earth Metal / Alloy 1), 2) (please specify)	A	B	C	D
	Amount of Rare Earth Production	Emission Factor	CF_4 Emissions	CF_4 Emissions
	(tonne rare earth metal produced)	(g CF_4/tonne metal produced)	(kg)	(Gg)
			$C = A * B /10^3$	$D = C/10^6$
Total				

1) Insert relevant rare earth metal or alloy, e.g.: Nd metal, Pr metal, Dy-Fe alloy, etc. For more details, refer to Section 4.8.1 in Volume 3, Chapter 4.

2) Insert additional rows if necessary.

(New Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Metal Industry - Rare Earths Production**			
Category Code	**2C7**			
Sheet	**3 of 4: C_2F_6 Emissions**			
Type of Rare Earth Metal / Alloy 1), 2) (please specify)	A	B	C	D
	Amount of Rare Earth Production	Emission Factor	C_2F_6 Emissions	C_2F_6 Emissions
	(tonne rare earth metal produced)	(g C_2F_6/tonne metal produced)	(kg)	(Gg)
			C = A * B /10^3	D = C/10^6
Total				

1) Insert relevant rare earth metal or alloy, e.g.: Nd metal, Pr metal, Dy-Fe alloy, etc. For more details, refer to Section 4.8.1 in Volume 3, Chapter 4.

2) Insert additional rows if necessary.

(New Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Metal Industry - Rare Earths Production**			
Category Code	**2C7**			
Sheet	**4 of 4: C_3F_8 Emissions**			
Type of Rare Earth Metal / Alloy 1), 2) (please specify)	A	B	C	D
	Amount of Rare Earth Production	Emission Factor	C_3F_8 Emissions	C_3F_8 Emissions
	(tonne rare earth metal produced)	(g C_3F_8/tonne metal produced)	(kg)	(Gg)
			C = A * B /10^3	D = C/10^6
Total				

1) Insert relevant rare earth metal or alloy, e.g.: Nd metal, Pr metal, Dy-Fe alloy, etc. For more details, refer to Section 4.8.1 in Volume 3, Chapter 4.

2) Insert additional rows if necessary.

2E ELECTRONICS INDUSTRY (UPDATED)

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Electronics Industry - Integrated Circuit or Semiconductor**
Category Code	**2E1**
Sheet	**1 of 3: Gaseous FC and N_2O Emissions**

Fluorinated Compounds (FCs)	A	B	C	D	E
	Annual Manufacturing Design Capacity or Actual Production[1)]	Annual Plant Production Capacity Utilization[1)]	Tier 1 Default FC Emission Factor[2)]	CO_2 Equivalent Conversion Factor[3)]	FC Emissions[4)]
	(Gm^2 of silicon processed)	(fraction)	(kg FC/m^2 of silicon processed)	(tonne CO_2 /tonne FC)	(Gg CO_2 equivalent)
					E = A * B * C * D * 10^3
CF_4			0.36		
C_2F_6			0.12		
C_3F_8			0.03		
C_4F_6			0.003		
c-C_4F_8			0.01		
C_4F_8O			7E-05		
C_5F_8			0.001		
CHF_3			0.05		
CH_2F_2			0.003		
NF_3			0.15		
SF_6			0.05		
N_2O			1.01		
Total					

1) If data on actual production are available, enter that data into column A and enter “1” into each cell in column B. The same value for capacity utilization should be entered in each row of column B, and the same value for capacity (or actual production) should be entered in each row of column A.

2) In using Tier 1, inventory compilers should not modify, in any way, the set of the FCs assumed here. 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 change the values of any factors in this column.

3) Typically, global warming potential (100 year time horizon) identified in the IPCC Assessment Report can be used. These factors should be the same as those used for other sectors/categories to ensure that they are all internally consistent in the inventory.

4) The Tier 1 method, unlike the Tier 3 or 2 methods, is designed to give an aggregated estimate of FC emissions although its methodology appears to produce gas-specific emissions.

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**				
Category	**Electronics Industry - Integrated Circuit or Semiconductor**				
Category Code	**2E1**				
Sheet	**2 of 3: Fluorinated Liquids from Heat Transfer Fluid Applications During Manufacturing**				
Fluorinated Liquids	A	B	C	D	E
	Annual Manufacturing Design Capacity or Actual Production1)	Annual Plant Production Capacity Utilization1)	Tier 1 Default FC Emission Factor 2)	CO_2 Equivalent Conversion Factor 3)	Fluorinated Liquids Emissions
	(Gm^2 of silicon consumed)	(fraction)	(kg/m^2)	(tonne CO_2 /tonne FC)	(Gg CO_2 equivalent)
					$E = A * B * C * D * 10^3$
HFE-449$_{sl}$			0.06		
C_6F_{14}			0.07		
PFPMIE			0.04		
Total					

1) If data on actual production are available, enter that data into column A and enter “1” into each cell in column B. The same value for capacity utilization should be entered in each row of column B, and the same value for capacity (or actual production) should be entered in each row of column A.

2) In using Tier 1, inventory compilers should not modify, in any way, the set of the fluorinated liquids assumed here. Inventory compilers should not combine emissions estimated using Tier 1 method with emissions estimated using the Tier 2 method. Neither may inventory compilers change the values of any factors in this column.

3) Typically, global warming potential (100 year time horizon) identified in the IPCC Assessment Report can be used. These factors should be the same as those used for other sectors/categories to ensure that they are all internally consistent in the inventory.

(New Worksheet)

Sector	**Industrial Processes and Product Use**				
Category	**Electronics Industry – Integrated Circuit or Semiconductor**				
Category Code	**2E1**				
Sheet	**3 of 3: Fluorinated Liquids from Testing, Packaging, and Soldering**				
Fluorinated Liquids	A	B	C	D	E
	Annual Manufacturing Design Capacity or Actual Production1)	Annual Plant Production Capacity Utilization1)	Tier 1 Default FC Emission Factor2)	CO_2 Equivalent Conversion Factor 2)	Fluorinated Liquids Emissions
	(Thousands of packaged devices)	(fraction)	(kg/kpcs)	(tonne CO_2 /tonne FC)	(Gg CO_2 equivalent)
					$E = (A * B * C * D)/10^6$
HFE-449_{sl}			1 x 10-4		
C_6F_{14}			3 x 10-5		
PFPMIE			1 x 10-5		
Total					

1) If data on actual production are available, enter that data into column A and enter “1” into each cell in column B. The same value for capacity utilization should be entered in each row of column B, and the same value for capacity (or actual production) should be entered in each row of column A.

2) In using Tier 1, inventory compilers should not modify, in any way, the set of the fluorinated liquids assumed here. Inventory compilers should not combine emissions estimated using Tier 1 method with emissions estimated using the Tier 2 method. Neither may inventory compilers change the values of any factors in this column.

3) Typically, global warming potential (100 year time horizon) identified in the IPCC Assessment Report can be used. These factors should be the same as those used for other sectors/categories to ensure that they are all internally consistent in the inventory.

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Electronics Industry - Display**
Category Code	**2E2**
Sheet	**1 of 2: Gaseous FC and N_2O Emissions**

Fluorinated Compounds (FCs)	A	B	C	D	E
	Annual Manufacturing Design Capacity or Actual Production[1)]	Annual Plant Production Capacity Utilization[1)]	Tier 1 Default FC Emission Factor[2)]	CO_2 Equivalent Conversion Factor[3)]	FC Emissions[4)]
	(Gm^2 of glass processed)	(fraction)	(g FC/array input glass area m^2)	(tonne CO_2 /tonne FC)	(Gg CO_2 equivalent)
					E = A * B * C * D
CF_4			0.65		
c-C_4F_8			0.001		
CHF_3			0.0024		
NF_3			1.29		
SF_6			4.14		
N_2O			17.06		
Total					

1) If data on actual production are available, enter that data into column A and enter “1” into each cell in column B. The same value for capacity utilization should be entered in each row of column B, and the same value for capacity (or actual production) should be entered in each row of column A.

2) In using Tier 1, inventory compilers should not modify, in any way, the set of the FCs assumed here. 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 change the values of any factors in this column.

3) Typically, global warming potential (100 year time horizon) identified in the IPCC Assessment Report can be used. These factors should be the same as those used for other sectors/categories to ensure that they are all internally consistent in the inventory.

4) The Tier 1 method, unlike the Tier 3 or 2 methods, is designed to give an aggregated estimate of FC emissions although its methodology appears to produce gas-specific emissions.

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**				
Category	**Electronics Industry - Display**				
Category Code	**2E2**				
Sheet	**2 of 2: Fluorinated Liquids from Heat Transfer Fluid Applications During Manufacturing**				
Fluorinated Liquids	A	B	C	D	E
	Annual Manufacturing Design Capacity Or Actual Production1)	Fraction of Annual Plant Production Capacity Utilization1)	Tier 1 Default FC Emission Factor 2)	CO_2 Equivalent Conversion Factor 3)	Fluorinated Liquids Emissions
	(Gm^2 of glass processed)	(fraction)	(kg/m^2)	(tonne CO_2 /tonne FC)	(Gg CO_2 equivalent)
					$E = A * B * C * D * 10^3$
HFE-449_{sl}			0.00002		
C_6F_{14}			0.00004		
PFPMIE			0.00004		
Total					

1) If data on actual production are available, enter that data into column A and enter “1” into each cell in column B. The same value for capacity utilization should be entered in each row of column B, and the same value for capacity (or actual production) should be entered in each row of column A.

2) In using Tier 1, inventory compilers should not modify, in any way, the set of the fluorinated liquids assumed here. Inventory compilers should not combine emissions estimated using Tier 1 method with emissions estimated using the Tier 2 method. Neither may inventory compilers change the values of any factors in this column.

3) Typically, global warming potential (100 year time horizon) identified in the IPCC Assessment Report can be used. These factors should be the same as those used for other sectors/categories to ensure that they are all internally consistent in the inventory.

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Electronics Industry - Photovoltaics**
Category Code	**2E3**
Sheet	**1 of 2: Gaseous FC Emissions**

Fluorinated Compounds (FCs)	A	B	C
	Annual Manufacturing Design Capacity or Actual Production1)	Fraction of Annual Plant Production Capacity Utilization1)	Fraction of PV manufacture that uses fluorinated compounds
	(Mm^2 of substrate processed)	(fraction)	(fraction)
CF_4			
C_2F_6			
Total			

1) If data on actual production are available, enter that data into column A and enter “1” into each cell in column B. The same value for capacity utilization should be entered in each row of column B, and the same value for capacity (or actual production) should be entered in each row of column A.

(Updated Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Electronics Industry - Photovoltaics**
Category Code	**2E3**
Sheet	**2 of 2: Gaseous FC Emissions**

Fluorinated Compounds (FCs)	D	E	F
	Tier 1 Default FC Emission Factor1)	CO_2 Equivalent Conversion Factor2)	FC Emissions3)
	(g FC/m^2 of substrate processed)	(tonne CO_2 /tonne FC)	(Gg CO_2 equivalent)
			$F = A * B * C * D * E / 10^3$
CF_4	5		
C_2F_6	0.2		
Total			

1) In using Tier 1, inventory compilers should not modify, in any way, the set of the FCs assumed here. 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 change the values of any factors in this column.

2) Typically, global warming potential (100 year time horizon) identified in the IPCC Assessment Report can be used. These factors should be the same as those used for other sectors/categories to ensure that they are all internally consistent in the inventory.

3) The Tier 1 method, unlike the Tier 3 or 2 methods, is designed to give an aggregated estimate of FC emissions although its methodology appears to produce gas-specific emissions.

(New Worksheet)

Sector	**Industrial Processes and Product Use**				
Category	**Electronics Industry – Microelectromechanical Systems (MEMS)**				
Category Code	**2E4**				
Sheet	**1 of 3: Gaseous FC Emissions**				
Fluorinated Compounds (FCs)	A	B	C	D	E
	Annual Manufacturing Design Capacity or Actual Production 1)	Annual Plant Production Capacity Utilization 1)	Tier 1 Default FC Emission Factor 2)	CO_2 Equivalent Conversion Factor 3)	FC Emissions 4)
	(Gm^2 of silicon processed)	(fraction)	(kg FC/m^2)	(tonne CO_2 /tonne FC)	(Gg CO_2 equivalent)
					E = A * B * C * D * 10^3
CF_4			0.015		
c-C_4F_8			0.076		
SF_6			1.86		
Total					

1) If data on actual production are available, enter that data into column A and enter “1” into each cell in column B. The same value for capacity utilization should be entered in each row of column B, and the same value for capacity (or actual production) should be entered in each row of column A.

2) In using Tier 1, inventory compilers should not modify, in any way, the set of the FCs assumed here. 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 change the values of any factors in this column.

3) Typically, global warming potential (100 year time horizon) identified in the IPCC Assessment Report can be used. These factors should be the same as those used for other sectors/categories to ensure that they are all internally consistent in the inventory.

4) The Tier 1 method, unlike the Tier 3 or 2 methods, is designed to give an aggregated estimate of FC emissions although its methodology appears to produce gas-specific emissions.

(New Worksheet)

Sector	**Industrial Processes and Product Use**				
Category	**Electronics Industry – Microelectromechanical Systems (MEMS)**				
Category Code	**2E4**				
Sheet	**2 of 3: Fluorinated Liquids from Heat Transfer Fluid Applications During Manufacturing**				
Fluorinated Liquids	A	B	C	D	E
	Annual Manufacturing Design Capacity or Actual Production1)	Annual Plant Production Capacity Utilization1)	Tier 1 Default FC Emission Factor2)	CO_2 Equivalent Conversion Factor 3)	Fluorinated Liquids Emissions
	(Gm^2 of silicon consumed)	(fraction)	(kg/m^2)	(tonne CO_2 /tonne FC)	(Gg CO_2 equivalent)
					$E = A * B * C * D * 10^3$
HFE-449_{sl}			0.06		
C_6F_{14}			0.07		
PFPMIE			0.04		
Total					

1) If data on actual production are available, enter that data into column A and enter “1” into each cell in column B. The same value for capacity utilization should be entered in each row of column B, and the same value for capacity (or actual production) should be entered in each row of column A.

2) In using Tier 1, inventory compilers should not modify, in any way, the set of the fluorinated liquids assumed here. Inventory compilers should not combine emissions estimated using Tier 1 method with emissions estimated using the Tier 2 method. Neither may inventory compilers change the values of any factors in this column.

3) Typically, global warming potential (100 year time horizon) identified in the IPCC Assessment Report can be used. These factors should be the same as those used for other sectors/categories to ensure that they are all internally consistent in the inventory.

(New Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Electronics Industry – Microelectromechanical Systems (MEMS)**
Category Code	**2E4**
Sheet	**3 of 3: Fluorinated Liquids from Testing, Packaging, and Soldering**

Fluorinated Liquids	A	B	C	D	E
	Annual Manufacturing Design Capacity or Actual Production[1)]	Annual Plant Production Capacity Utilization[1)]	Tier 1 Default FC Emission Factor[2)]	CO_2 Equivalent Conversion Factor [3)]	Fluorinated Liquids Emissions
	(Thousands of packaged devices)	(fraction)	(kg/kpcs)	(tonne CO_2 /tonne FC)	(Gg CO_2 equivalent)
					$E = (A * B * C * D)/10^6$
$HFE\text{-}449_{sl}$			1 x 10-4		
C_6F_{14}			3 x 10-5		
PFPMIE			1 x 10-5		
Total	▨	▨	▨	▨	

1) If data on actual production are available, enter that data into column A and enter “1” into each cell in column B. The same value for capacity utilization should be entered in each row of column B, and the same value for capacity (or actual production) should be entered in each row of column A.

2) In using Tier 1, inventory compilers should not modify, in any way, the set of the fluorinated liquids assumed here. Inventory compilers should not combine emissions estimated using Tier 1 method with emissions estimated using the Tier 2 method. Neither may inventory compilers change the values of any factors in this column.

3) Typically, global warming potential (100 year time horizon) identified in the IPCC Assessment Report can be used. These factors should be the same as those used for other sectors/categories to ensure that they are all internally consistent in the inventory.

2G2 OTHER PRODUCT MANUFACTURE AND USE - SF$_6$ AND PFCS FROM OTHER PRODUCT USES (UPDATED)

The sheet 7 of 8 is introduced, so it changes the numbering of worksheets.

(Unchanged Worksheet)

Sector	**Industrial Processes and Product Use**		
Category	**Other Product Manufacture and Use - SF$_6$ and PFCs from Other Product Uses**		
Category Code	**2G2**		
Sheet	**1 of 8 SF$_6$ Emissions from Military Applications (AWACS)**		
A	B	C	D
National AWACS Fleet	Emission Factor	SF$_6$ Emissions	SF$_6$ Emissions
(number of AWACS)	(kg SF$_6$/plane)	(kg)	(Gg)
		C = A * B	D = C/10^6

(Unchanged Worksheet)

Sector	**Industrial Processes and Product Use**				
Category	**Other Product Manufacture and Use - SF$_6$ and PFCs from Other Product Uses**				
Category Code	**2G2**				
Sheet	**2 of 8 SF$_6$ Emissions from University and Research Particle Accelerators**				
A	B	C	D	E	F
Number of University and Research Particle Accelerators in the Country	SF$_6$ Use Factor	SF$_6$ Charge Factor	SF$_6$ Emission Factor	SF$_6$ Emissions	SF$_6$ Emissions
(number)	(fraction)	(kg SF$_6$/particle accelerator)	(fraction)	(kg)	(Gg)
				E = A * B * C * D	F = E/10^6

(Unchanged Worksheet)

Sector	**Industrial Processes and Product Use**				
Category	**Other Product Manufacture and Use - SF_6 and PFCs from Other Product Uses**				
Category Code	**2G2**				
Sheet	**3 of 8 SF_6 Emissions from Industrial and Medical Particle Accelerators**				
Process Description	A	B	C	D	E
	Number of Particle Accelerators that use SF_6 by Process Description in the Country	SF_6 Charge Factor	SF_6 Emission Factor	SF_6 Emissions	SF_6 Emissions
	(number)	(kg SF_6/particle accelerator)	(fraction)	(kg)	(Gg)
				D = A * B * C	$E = D/10^6$
Industrial Accelerator (High Voltage: 0.3-23 MV)					
Industrial Accelerator (Low Voltage: <0.3 MV)					
Medical					
Total					

(Unchanged Worksheet)

Sector	**Industrial Processes and Product Use**		
Category	**Other Product Manufacture and Use - SF_6 and PFCs from Other Product Uses**		
Category Code	**2G2**		
Sheet	**4 of 8 SF_6 Emissions[1)] from Adiabatic Uses**		
Type of Applications[2), 3)] (please specify)	A	B	C
	Sales into application in year t-3	SF_6 Emissions in year t	SF_6 Emissions in year t
	(tonne)	(tonne)	(Gg)
		B = A	$C = B/10^3$
Total			

1) Emissions of PFCs can be estimated by the same calculation procedure.

2) For example, car tires, sport shoe soles and tennis balls.

3) Insert additional rows, if necessary.

(Unchanged Worksheet)

Sector	**Industrial Processes and Product Use**				
Category	**Other Product Manufacture and Use - SF$_6$ and PFCs from Other Product Uses**				
Category Code	**2G2**				
Sheet	**5 of 8 SF$_6$ Emissions from Sound-Proof Glazing**				
A	B	C	D	E	F
SF$_6$ Purchased to Fill Windows Assembled in Inventory Year	Assembly Emission Factor	Assembly Emissions	Capacity of Existing Windows in Inventory Year	Leakage Emission Factor	Leakage Emissions
(tonne SF$_6$)	(fraction)	(tonne SF$_6$)	(tonne SF$_6$)	(fraction)	(tonne SF$_6$)
		C = A * B			F = D * E

(Unchanged Worksheet)

Sector	**Industrial Processes and Product Use**			
Category	**Other Product Manufacture and Use - SF$_6$ and PFCs from Other Product Uses**			
Category Code	**2G2**			
Sheet	**6 of 8 SF$_6$ Emissions from Sound-Proof Glazing**			
G	H	I	J	K
Amount Left in Windows at End of Lifetime (Disposed of in Inventory Year)	Recovery Factor1)	Disposal Emissions	Total Emissions	Total Emissions
(tonne SF$_6$)	(fraction)	(tonne SF$_6$)	(tonne SF$_6$)	(Gg SF$_6$)
		I = G * (1 – H)	J = C + F + I	K = J/10^3
1) Recovery factor is assumed to be zero unless country-specific information is available.				

(New Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Other Product Manufacture and Use - SF_6 and PFCs from Other Product Uses**
Category Code	**2G2**
Sheet	**7 of 8 Emissions of PFCs from Waterproofing of Electronic Circuits**

Fluorinated Compounds (FCs)	A	B	C	D	E	F
	Number of circuit boards manufactured	Emission Factor	Emissions in g	Emissions in Gg	CO_2 Equivalent Conversion Factor[1]	FC Emissions)
		(g/circuit board)	(g)	(Gg)	(Gg CO_2 /Gg FC)	(Gg CO_2 equivalent)
			C = A * B	$D = C/10^9$		F = D * E
CF_4						
C_2F_6						
CHF_3						
Total						

1) Typically, global warming potential (100 year time horizon) identified in the IPCC Assessment Report can be used. These factors should be the same as those used for other sectors/categories to ensure that they are all internally consistent in the inventory

(Unchanged Worksheet)

Sector	**Industrial Processes and Product Use**
Category	**Other Product Manufacture and Use - SF_6 and PFCs from Other Product Uses**
Category Code	**2G2**
Sheet	**8 of 8 Emissions of SF_6 and PFCs from Other Prompt Emissive Applications**

Type of Applications 1), 2) (please specify)	A	B	C	D
	Sales into application in year t	Sales into application in year t-1	Emissions in year t	Emissions in year t
	(tonne)	(tonne)	(tonne)	(Gg)
			C = 0.5 * (A + B)	$D = C/10^3$
Total				

1) For example, tracers and use in production of optical cables.

2) Insert additional rows, if necessary.

ANNEX 4

GLOSSARY FOR INDUSTRIAL PROCESSES AND PRODUCT USE SECTOR

ANNEX 4 GLOSSARY FOR INDUSTRIAL PROCESSES AND PRODUCT USE SECTOR

This annex provides new definitions and abbreviations for terms used in this volume on Industrial Processes and Product Use (IPPU) Sector (Annex 4 Volume 3 of the *2019 Refinement*).

This annex should be used in conjunction with glossary in Annex 4 of Volume 3 of the *2006 IPCC Guidelines* and general glossary of the *2006 IPCC Guidelines* and the *2019 Refinement*.

Glossary (new)

ANODE EFFECT (HIGH VOLTAGE & LOW VOLTAGE ANODE EFFECT)

In primary aluminium and rare earth metals production (by fluoride electrolysis), an anode effect is a process upset condition where an insufficient amount of metal oxide (alumina in aluminium production, rare earth oxides in rare earth metal production) is dissolved in the electrolyte, resulting in the emission of PFC gases. This often causes voltage on industrial cells to be elevated above the normal operating range; however, PFC gases can also be generated in the absence of elevated voltage. A high voltage anode effect (HVAE) corresponds to emissions of PFCs gases when the cell voltage exceeds the specific voltage threshold defined for anode effects at the facility (e.g. >8 volts for aluminium production). A low voltage anode effect (LVAE) corresponds to emission of PFC gases in cases where the cell voltage doesn't exceed the voltage threshold (e.g. <8 volts for aluminium production).

ODS-SUBSTITUTES

Alternatives to Ozone Depleting Substances, for instance HFCs

RARE EARTH

Rare earth elements or rare earth metals (REM) are a group of 17 chemically similar metallic elements in the periodic table, i.e.: scandium (Sc), yttrium (Y) and the lanthanides – lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu). 'Rare earths' typically refers to the rare earth oxide.

Abbreviation (new)

HVAE	High Voltage Anode Effect
LVAE	Low Voltage Anode Effect
PFC	Perfluorocarbon gases
RE	Rare Earth
REO	Rare Earth Oxide

ANNEX 5

MAPPING TABLES

Contents

Annex 5. Relating 2019 Refinement to the 2006 IPCC Guidelines

This annex provides a road map for relating sections, equations, tables, figures and boxes in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

Type of Refinement: U – Update, NG – New Guidance, NR – No Refinement.

CHAPTER 1 INTRODUCTION

Sections

- The sections 1.1 and 1.2 were updated to refine the list of IPPU categories and gases.
- The section 1.3 and 1.4 were updated to refine the non-energy use of fuels in new categories. (e.g. Hydrogen Production)

Section Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Section Number**	***2019 Refinement*** **Section Number**
Sub-Chapter 1.1	U	1.1	1.1
Sub-Chapter 1.2			
Definition of industrial process and, fuel combustion and fuel transformation emissions	U	1.2.1	1.2.1
Capture and abatement	NR	1.2.2	1.2.2
Precursors	NR	1.2.3	1.2.3
Indirect N_2O	NR	1.2.4	1.2.4
International data sources	NR	1.2.5	1.2.5
Sub-Chapter 1.3	U	1.3	1.3
Types of uses	U	1.3.1	1.3.1
Accounting for feedstock and reductant uses of fossil fuels and their CO_2 emissions	NR	1.3.2	1.3.2
Emissions from refinery processes	U	1.3.3	1.3.3
Sub-Chapter 1.4			
Introduction	NR	1.4.1	1.4.1
Scope of methods	NR	1.4.2	1.4.2
Quality control of completeness	U	1.4.3	1.4.3
Reporting and documentation of allocation and QC of completeness	U	1.4.4	1.4.4
Sub-Chapter 1.5	NR	1.5	1.5

Equations

Equation Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Equation Number**	***2019 Refinement*** **Equation Number**
Sub-Chapter 1.4			
Total feedstock requirement	NR	1.1	1.1

Tables

Table Title	**Type of Refinement**	***2006 IPCC Guidelines* Table Number**	***2019 Refinement* Table Number**
Sub-Chapter 1.2			
Industrial Processes and Product Use categories and their possible emissions	U	1.1	1.1
Sub-Chapter 1.3			
Types of use and examples of fuels used for non-energy applications	U	1.2	1.2
Sub-Chapter 1.3			
Verification of completeness of reported CO_2 from non-energy use of fuels	U	1.3	1.3
List of fuels that can be used as chemical feedstock or reductant	U	1.4	1.4
Comparison of feedstock supply with requirements implied by production	U	1.5a	1.5a
Specific Feedstock Consumption (TJ/Gg) for feedstock/reductants	U	1.5b	1.5b
Allocation of CO_2 from non-energy use of fossils fuels: IPPU and other Sectors	U	1.6	1.6

Figures

Figure Title	**Type of Refinement**	***2006 IPCC Guidelines* Figure Number**	***2019 Refinement* Figure Number**
Sub-Chapter 1.1			
Industrial Processes and Product Use categories	U	1.1	1.1
Sub-Chapter 1.3			
General material balance of industrial processes where products are made using hydrocarbon feedstock (size of flows arbitrarily chosen). (Adapted from Neelis et al., 2005)	NR	1.2	1.2
Sub-Chapter 1.4			
Flowchart for verification of completeness of accounting for non-energy uses of fuels	NR	1.3	1.3

Boxes

Box Title	**Type of Refinement**	***2006 IPCC Guidelines* Box Number**	***2019 Refinement* Box Number**
Sub-Chapter 1.2			
Allocation of CO_2 emissions to fuel combustion or industrial process emissions	NR	1.1	1.1

CHAPTER 3 CHEMICAL INDUSTRY EMISSIONS

Sections

- The section, 3.3.2.2, is an update of section 3.3.2.2 Chapter 3 Volume 3 of *2006 IPCC Guidelines* and should be used instead of the section 3.3.2.2 Chapter 3 Volume 3 of *2006 IPCC Guidelines*.
- The section, 3.10.1.2, is an update of section 3.10.1.2 Chapter 3 Volume 3 of *2006 IPCC Guidelines* and should be used instead of the section 3.10.1.2 Chapter 3 Volume 3 of the *2006 IPCC Guidelines*. To remain consistent with the updated terminology in section 3.10.2, the terminology used for the Tier 3 method in this section has been updated to refer to the development and use of an “emission factor method” rather than a “proxy method.” In addition, the lower bound emission factor presented for optimised plants has been updated to reflect the value that in the Annex 3A.1.
- The section, 3.10.1.3, is an update of section 3.10.1.3 Chapter 3 Volume 3 of *2006 IPCC Guidelines* and should be used instead of the section 3.10.1.3 Chapter 3 Volume 3 of *2006 IPCC Guidelines*. This section has been updated to refer to the “emission factor method” rather than the “proxy method.
- The section, 3.10.2.1, is an update of section 3.10.2.1 Chapter 3 Volume 3 of *2006 IPCC Guidelines* and should be used instead of the section 3.10.1.2 Chapter 3 Volume 3 of *2006 IPCC Guidelines*. This section has been updated to clarify the full range of emissions and their sources at fluorochemical production plants.
- The section, 3.10.2.2, is an update of section 3.10.2.2 Chapter 3 Volume 3 of *2006 IPCC Guidelines* and should be used instead of the section 3.10.2.2 Chapter 3 Volume 3 of *2006 IPCC Guidelines*. The section has been updated with guidance for the Tier 3 method that now includes a method to estimate emissions from equipment leaks and more detail to the method for estimating emissions from process vents. New default emission factors are presented for the Tier 1 method.
- This section, 3.10.2.3, is an update of section 3.10.2.3 Chapter 3 Volume 3 of the *2006 IPCC Guidelines* and should be used instead of the section 3.10.2.3 Chapter 3 Volume 3 of the *2006 IPCC Guidelines*.
- The section, 3.11, is a new section in the Chapter 3 Volume 3 of the *2019 Refinement*. It should be placed after section 3.10 Chapter 3 Volume 3 of the *2006 IPCC Guidelines*.
- New Annex was introduced - Annex 3A.1 “Default emission factor for section 3.10.2 Emissions from production of fluorinated compounds (other than HFC-23 emissions from HCFC-22 production)”. This annex provides background information for the Tier 1 default emission factors for fluorinated greenhouse gases (GHG) from fluorochemical production, that are provided in section 3.10.2 in the *2019 Refinement* to the *2006 IPCC Guidelines*. The first section discusses the default emission factors for SF_6 and NF_3 production based on literature search, and the second section discusses the default emission factor estimated from the data reported to the U.S. Greenhouse Gas Reporting Program.

Section Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Section Number**	***2019 Refinement*** **Section Number**
Sub-Chapter 3.3			
Choice of emission factors	U	3.3.2.2	3.3.2.2
Sub-Chapter 3.10			
Introduction	NR	3.10.1.1	3.10.1.1
Methodological issues	U	3.10.1.2	3.10.1.2
Uncertainty assessment	U	3.10.1.3	3.10.1.3
Quality assurance/quality control (QA/QC), reporting and documentation	NR	3.10.1.4	3.10.1.4
Introduction	U	3.10.2.1	3.10.2.1
Methodological issues	U	3.10.2.2	3.10.2.2
Uncertainty assessment	U	3.10.2.3	3.10.2.3
Quality assurance/quality Control (QA/QC), reporting and documentation	NR	3.10.2.4	3.10.2.4

Section Title	Type of Refinement	*2006 IPCC Guidelines* Section Number	*2019 Refinement* Section Number
Sub-Chapter 3.11			
Hydrogen Production	NG	-	3.11
Annex 3A.1			
Default emission factor for section 3.10.2 Emissions from production of fluorinated compounds (other than HFC-23 emissions from HCFC-22 production)	NG	-	Annex 3A.1

Equations

Equation Title	Type of Refinement	*2006 IPCC Guidelines* Equation Number	*2019 Refinement* Equation Number
Sub-Chapter 3.3			
No refinements	NR	-	-
Sub-Chapter 3.10			
Tier 1 calculation of HFC-23 from HCFC-22 (produced) using default factor	NR	3.30	3.30
Tier 2 calculation of HFC-23 from HCFC-22 (produced) using factor(s) calculated from process efficiencies	NR	3.31	3.31
Calculation of HFC-23 emission factor from carbon balance efficiency	NR	3.32	3.32
Calculation of HFC-23 emission factor from fluorine balance efficiency	NR	3.33	3.33
Tier 3a calculation of HFC-23 emissions from individual process streams (direct method)	NR	3.34	3.34
Tier 3b calculation of HFC-23 emissions from individual process streams using a Site- Or Process-Specific Emission Factor	U	3.35	3.35
Tier 3c calculation of HFC-23 emissions from individual process streams (by monitoring reactor product)	NR	3.36	3.36
Tier 3a calculation of ‘instantaneous’ HFC-23 emissions in an individual process stream (direct method)	NR	3.37	3.37
Tier 3b calculation of HFC-23 emissions in an individual process stream using a Site- Or Process-Specific Emission Factor	U	3.38	3.38
Tier 3b calculation of standard emission for Emission Factor-based method	U	3.39	3.39
Tier 3c calculation of HFC-23 emissions from an individual facility by in-process measurement	NR	3.40	3.40
Tier 1 calculation of production-related emissions	NR	3.41	3.41
Tier 2 calculation of production-related emissions using a mass balance approach	NG	-	3.41a

Equation Title	**Type of Refinement**	***2006 IPCC Guidelines* Equation Number**	***2019 Refinement* Equation Number**
Tier 3 summation of production-related emissions from process vents and equipment leaks	NG	-	3.41b
Tier 3 direct calculation of production-related emissions from process vents	U	3.42	3.42
Tier 3 calculation of production-related emissions from process vents using a Site- Or Process-Specific Emission Factor	U	3.43	3.43
Tier 3 calculation of emissions from equipment leaks using a Screening Ranges Approach	NG	-	3.43a
Tier 3 calculation of emissions from equipment leaks using a Correlation Approach	NG	-	3.43b
Tier 3 calculation of a Unit-specific Correlation	NG	-	3.43c
Tier 3 calculation of emissions from equipment leaks using a Unit-specific Correlation Approach	NG	-	3.43d
Tier 3 calculation of production-related emissions from equipment leaks	NG	-	3.43e
Sub-Chapter 3.11			
All equations are new	NG	-	3.44-3.50

Tables

Table Title	**Type of Refinement**	***2006 IPCC Guidelines* Table Number**	***2019 Refinement* Table Number**
Sub-Chapter 3.3			
Different plant types for the production of HNO_3	NG	-	3.3.a
Default factors for nitric acid production	U	3.3	3.3
Sub-Chapter 3.10			
HFC-23 default emission factors	U	3.28	3.28
Tier 1 default emission factor for fluorochemical production	NG	-	3.28a
Representative chemical composition of the emitted mass	NG	-	3.28b
Sub-Chapter 3.11			
All tables are new	NG	-	3.29-3.30

Figures

Figure Title	**Type of Refinement**	***2006 IPCC Guidelines* Figure Number**	***2019 Refinement* Figure Number**
Sub-Chapter 3.3			
No refinements	NR	-	-
Sub-Chapter 3.10			
Decision tree for HFC-23 emissions from HCFC-22 production (or other similar by-product emissions from fluorochemical production)	NR	3.16	3.16
Decision tree for emissions of fluorinated greenhouse gas from fluorochemical production processes, applicable to product, by-product, reactant, and fugitive emissions	U	3.17	3.17
Sub-Chapter 3.11			
All figures are new	NG	-	3.18-3.20

Boxes

Box Title	**Type of Refinement**	***2006 IPCC Guidelines* Box Number**	***2019 Refinement* Box Number**
Sub-Chapter 3.10			
Plant measurement frequency	NR	3.14	3.14
Sub-Chapter 3.11			
All boxes are new	NG	-	3.15-3.19

CHAPTER 4 METAL INDUSTRY EMISSIONS

Sections

- The section, 4.2.2, is an update of section 4.2.2 Chapter 4, Volume 3 of the *2006 IPCC Guidelines* and should be used instead of the section 4.2.2 Chapter 4, Volume 3 of the *2006 IPCC Guidelines*.
- The section, 4.2.3, is an update of section 4.2.3 Chapter 4, Volume 3 of the *2006 IPCC Guidelines* and should be used instead of the section 4.2.3 Chapter 4, Volume 3 of the *2006 IPCC Guidelines*.
- The sub-chapter, 4.4, for primary aluminium production is an update of sub-chapter 4.4, Chapter 4, Volume 3 of the *2006 IPCC Guidelines* and should be used instead of sub-chapter 4.4, Chapter 4, Volume 3 of the *2006 IPCC Guidelines*, with only two exceptions: sections 4.4.2.1 and 4.4.2.2 (regarding process CO_2 emissions from primary aluminium production) have no refinements and these sections in the existing *2006 IPCC Guidelines* should be used. Updates and new guidance in the rest of sub-chapter 4.4 include:
    - (i) Section 4.4.1 is an updated introduction to GHG emissions from primary aluminium production, including alumina refining via alternative Bayer-Sinter and Nepheline technologies.
    - (ii) Sections 4.4.2.3 to 4.4.2.7 and sections 4.4.3 to 4.4.4 provide updates and new guidance relating to perfluorocarbon (PFC) emissions from primary aluminium production. These include:
        - Updated technology classes for accounting PFC emissions only.
        - Updated guidance (including Tier 1-2 default factors and uncertainties) for PFC emissions from ‘high voltage anode effects’ (HVAE), previously termed ‘anode effects’ in the *2006 IPCC Guidelines*. This includes a new Tier 2b-3b methodology.
        - New guidance on PFC emissions from ‘low voltage anode effects’ (LVAE), using either default (Tier 1) or facility-specific (Tier 3c) emission factors, based on maturity of literature at cut-off date.
        - New guidance on accounting PFC emissions during cell start-up (CSU) periods, if not already accounted for in HVAE and LVAE emissions.
        - New guidance on Total PFC emissions, being the sum of HVAE, LVAE and CSU emissions
        - A new Tier 3e facility-specific methodology for total PFC emissions by gas measurement.
        - Corresponding updates relating to Time-Series Consistency, Uncertainty Assessment and QA/QC Reporting and Documentation sections.
    - (iii) Sections 4.4.5 to 4.4.7 provide new guidance relating to GHG emissions from alumina production via alternative Bayer-Sinter and Nepheline processes. It follows on from section 4.4.4, Chapter 4, Volume 3 of the *2006 IPCC Guidelines*.
- The sub-chapter, 4.8, provides new guidance for primary rare earth (RE) metal production. Since there is no existing guidance in the *2006 IPCC Guidelines*, this is an entirely new sub-chapter 4.8 and follows on from sub-chapter 4.7, Chapter 4, Volume 3 of the *2006 IPCC Guidelines*.

Sections

Section Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Section Number**	***2019 Refinement*** **Section Number**
Sub-Chapter 4.2			
Introduction	NR	4.2.1	4.2.1
Methodological issues	U	4.2.2	4.2.2
Choice of method: metallurgical coke production	U	4.2.2.1	4.2.2.1
Choice of method: iron and steel production	U	4.2.2.2	4.2.2.2
Choice of emission factors	U	4.2.2.3	4.2.2.3
Choice of activity data	U	4.2.2.4	4.2.2.4
Completeness	U	4.2.2.5	4.2.2.5
Developing a consistent time series	NR	4.2.2.6	4.2.2.6
Uncertainty assessment	U	4.2.3	4.2.3
Quality Assurance/Quality Control (QA/QC), Reporting and Documentation	NR	4.2.4	4.2.4
Sub-Chapter 4.4			
Introduction	U	4.4.1	4.4.1
Choice of method for CO_2 emissions from primary aluminium production	NR	4.4.2.1	4.4.2.1
Choice of emission factors for CO_2 emissions from primary aluminium production	NR	4.4.2.2	4.4.2.2
Choice of method for PFCs	U	4.4.2.3	4.4.2.3
Choice of emission factors for PFCs	U	4.4.2.4	4.4.2.4
Choice of activity data	U	4.4.2.5	4.4.2.5
Completeness	U	4.4.2.6	4.4.2.6
Developing a consistent time series	U	4.4.2.7	4.4.2.7
Uncertainty assessment for primary aluminium production	U	4.4.3	4.4.3
Emission factor uncertainties	U	4.4.3.1	4.4.3.1
Activity data uncertainties	U	4.4.3.2	4.4.3.2
Quality assurance/quality control (QA/QC)	U	4.4.4.1	4.4.4.1
Reporting and documentation	U	4.4.4.2	4.4.4.2
Methodological issues for alumina production	NG	-	4.4.5
Alternative alumina refining processes	NG		4.4.5.1
Choice of method for alumina production	NG	-	4.4.5.2
Choice of emission factors for alumina production	NG	-	4.4.5.3
Choice of activity data	NG	-	4.4.5.4
Completeness	NG	-	4.4.5.5
Developing a consistent time series	NG	-	4.4.5.6
Uncertainty assessment for alumina production	NG	-	4.4.6
Emission factor uncertainties	NG	-	4.4.6.1
Activity data uncertainties	NG	-	4.4.6.2

Section Title	**Type of Refinement**	***2006 IPCC Guidelines* Section Number**	***2019 Refinement* Section Number**
Quality assurance/quality control (QA/QC)	NG	-	4.4.7.1
Reporting and documentation	NG	-	4.4.7.2
Sub-Chapter 4.8			
Rare earths production (and all sub-sections included)	NG	-	4.8

Equations

Equation Title	**Type of Refinement**	***2006 IPCC Guidelines* Equation Number**	***2019 Refinement* Equation Number**
Sub-Chapter 4.2			
CO_2 emissions from coke production (Tier 1a)	U	4.1	4.1
CH_4 emissions from coke production (Tier 1a)	NG	-	4.1a
CO_2 emissions from metallurgical coke production (Tier 1b)	NG	-	4.1b
CO_2 emissions from metallurgical coke production (Tier 2)	U	4.2	4.2
CO_2 emissions from iron and steel production (Tier 1)	NR	4.4	4.4
CO_2 emissions from production of pig iron not processed into steel (Tier 1)	NR	4.5	4.5
CO_2 emissions from production of direct reduced iron (Tier 1)	NR	4.6	4.6
CO_2 emissions from sinter production (Tier 1)	NR	4.7	4.7
CO_2 emissions from pellet production (Tier 1)	NR	4.8	4.8
CO_2 emissions from BFG and LDG flaring (Tier 1)	NG	-	4.8a
CO_2 emissions from iron & steel production (Tier 2)	U	4.9	4.9
CO_2 emissions from sinter production (Tier 2)	U	4.10	4.10
CO_2 emissions from direct reduced iron production (Tier 2)	NR	4.11	4.11
CH_4 emissions from sinter production (Tier 1)	NR	4.12	4.12
CH_4 emissions from blast furnace production of pig iron (Tier 1)	NR	4.13	4.13
CH_4 emissions from direct reduced iron production (Tier 1)	NR	4.14	4.14
N_2O emissions from flaring (Tier 1)	NG	-	4.14a
Sub-Chapter 4.4			
Process CO_2 emissions from anode and/or paste consumption (tier 1 method)	NR	4.20	4.20
CO_2 emissions from prebaked anode consumption (tier 2 and tier 3 methods)	NR	4.21	4.21
CO_2 emissions from pitch volatiles combustion (tier 2 and tier 3 methods)	NR	4.22	4.22

Equations (Continued)

Equation Title	Type of Refinement	*2006 IPCC Guidelines* Equation Number	*2019 Refinement* Equation Number
CO_2 emissions from bake furnace packing material (tier 2 and tier 3 methods)	NR	4.23	4.23
CO_2 emissions from paste consumption (tier 2 and tier 3 methods)	NR	4.24	4.24
Total PFC Emissions	NG	-	4.24a
HVAE PFC emissions (Tier 1 method)	U	4.25	4.25
HVAE PFC emissions by Slope method (Tier 2a and Tier 3a methods)	U	4.26	4.26
HVAE PFC emissions by Overvoltage method (Tier 3a method)	U	4.27	4.27
HVAE PFC emissions (Tier 2b and Tier 3b method – (Marks & Nunez 2018a))	NG	-	4.27a
HVAE PFC emissions (Tier 2b and Tier 3b method – (Dion *et al.* 2018a))	NG	-	4.27b
LVAE PFC emissions (Tier 1 and Tier 3 methods – production-based)	NG	-	4.27c
LVAE PFC emissions (Tier 3 method – as ratio of HVAE emissions)	NG	-	4.27d
Total PFC emissions for start-up of electrolysis cells (Tier 3_{CSU} method)	NG	-	4.27e
Emission rate coefficients for HVAE PFC (Tier 2b method – (Dion *et al.* 2018a))	NG	-	4.27f
Tier 1: Sintering process emissions based on alumina production data	NG	-	4.27g
Tier 3: Emissions based on carbonate raw material inputs to the sintering kiln	NG	-	4.27h
Emissions captured during carbonization process and contained in produced sodium carbonate	NG	-	4.27i
Emissions from un-calcined SKD not recycled to the kiln	NG	-	4.27j
Weighted average content CO_2 in 'i' Bauxite (Nepheline) Ore	NG	-	4.27k
Potential emissions from Bauxites (Nephelines) residue	NG	-	4.27l
Emissions from carbon-bearing non-fuel materials	NG	-	4.27m
CO_2 absorption through use of circulating water collected from bauxite/nepheline storage residue area and/or absorption through bauxite residue neutralization	NG	-	4.27n
Sub-Chapter 4.8			
Process CO_2 emissions from anode consumption (Tier 1)	NG	-	4.35
Process CO_2 emissions from anode consumption (Tier 3)	NG	-	4.36
PFC emissions from rare earth metals production (Tier 1 and Tier 3)	NG	-	4.37

Tables

Table Title	**Type of Refinement**	***2006 IPCC Guidelines* Table Number**	***2019 Refinement* Table Number**
Sub-Chapter 4.2			
Emission allocations from metallurgical coke production	NG	-	4.1a
Tiers to estimate CO_2 emissions from metallurgical coke production – non fugitive emissions	NG	-	4.1b
Tier 1 default CO_2 emission factors for coke production	U	4.1	4.1
Tier 1 default CO_2 emission factors for sinter and pellet production	NG	-	4.1a
Tier 1 default CO_2 emission factors for iron and steel production	NG	-	4.1b
Tier 1 default CH_4 emission factors for coke production (non fugitives), iron and steel production	U	4.2	4.2
Tier 1 default N_2O emission factors for coke production and iron and steel production	NG	-	4.2b
Tier 2 material-specific carbon contents for iron and steel - production (tonnes C/tonne)	U	4.3	4.3
Uncertainty ranges	U	4.4	4.4
Sub-Chapter 4.4			
Tier 1 technology specific emission factors for calculating carbon dioxide emissions from anode or paste consumption	NR	4.10	4.10
Data sources and uncertainties for parameters used in tier 2 or 3 method for CO_2 emissions from prebake cells (CWPB and SWPB) , see equation 4.21	NR	4.11	4.11
Data sources and uncertainties for parameters used in tier 2 or 3 method for CO_2 emissions from pitch volatiles combustion (CWPB and SWPB)	NR	4.12	4.12
Data sources and uncertainties for parameters used in tier 2 or 3 method for CO_2 emissions from bake furnace packing material (CWPB and SWPB)	NR	4.13	4.13
Data sources and uncertainties for parameters used in tier 2 or 3 method for CO_2 emissions from Søderberg cells	NR	4.14	4.14
Summary of accounting methods for PFC emissions	NG	-	4.14a
Technology specific default emission factors for the calculation of HVAE and LVAE emissions from aluminium production (Tier 1 method)	U	4.15	4.15
Technology specific coefficients for the calculation of HVAE PFC emissions from aluminium production using slope methodology (Tier 2a method)	U	4.16	4.16
Specific HVAE-PFC emission rate coefficients based on the anode effect duration as calculated by (Marks & Nunez 2018a) (Tier 2b method)	NG	-	4.16a
Uncertainty range (percent) in estimating PFC emissions from individual HVAEs (Tier 2b methods)	NG	-	4.16b
Time period of measurements used to establish updated Tier 1 default EFs and Tier 2a default slope coefficients	NG	-	4.16c
Summary of which guidelines to refer to, for time consistent PFC inventories	NG	-	4.16d
Good practice reporting information for calculating CO_2 and PFC emissions from aluminium production by tier	U	4.17	4.17

Table Title	**Type of Refinement**	***2006 IPCC Guidelines* Table Number**	***2019 Refinement* Table Number**
Technology specific default emission factors for the calculation of CO_2 emissions from alternative sintering processes (Tier 1 method)	NG	-	4.17a
Default uncertainty values for Bauxite/nepheline sintering processes	NG	-	4.17b
Sub-Chapter 4.8			
Tier 1 default emission factors for calculating CO_2 emissions from anode consumption	NG	-	4.26
Data sources and uncertainties for parameters used in Tier 3 method for CO_2 emissions from anode consumption	NG	-	4.27
Tier 1 default emission factors and uncertainty ranges for the calculation of PFC emissions from rare earth production	NG	-	4.28
Data sources and uncertainties for parameters used in Tier 3 method for PFC emissions	NG	-	4.29
Good practice reporting information for calculating CO_2 and PFC emissions from rare earth metal production by Tier	NG	-	4.30

Figures

Figure Title	**Type of Refinement**	***2006 IPCC Guidelines* Figure Number**	***2019 Refinement* Figure Number**
Sub-Chapter 4.2			
Illustration of main processes for integrated iron and steel production	NR	4.1	4.1
Estimation of CO_2 emissions from metallurgical coke production	U	4.6	4.6
Decision tree for estimation of CO_2 emissions from iron and steel production	U	4.7	4.7
Decision tree for estimation of CH_4 emissions from coke production	NG	-	4.8a
Decision tree for estimation of CH_4 emissions from iron and steel production	U	4.8	4.8b
Decision tree for estimation of N_2O emissions from iron and steel production	NG	-	4.8c
Energy or IPPU CO_2 emissions allocation in an integrated iron and steel facility	NG	-	4.8d
Sub-Chapter 4.4			
Decision tree for calculation of CO_2 emissions from primary aluminium production	NR	4.11	4.11
Decision tree for calculation of HVAE related PFC emissions from primary aluminium production	U	4.12	4.12
Decision tree for calculation of LVAE related PFC emissions from primary aluminium production	NG	-	4.12a
Alumina production processes	NG	-	4.12b
Decision tree for estimation of CO_2 emissions from alumina production	NG	-	4.12c
Sub-Chapter 4.8			
Decision tree for calculation of CO_2 emissions from primary rare earth (RE) metal production.	NG	-	4.17
Decision tree for calculation of PFC emissions from primary rare earth (RE) metal production.	NG	-	4.18

Boxes

Box Title	**Type of Refinement**	***2006 IPCC Guidelines* Box Number**	***2019efinement* Box Number**
Sub-Chapter 4.2			
Flaring activities in metallurgical coke and iron and steel production	NG	-	4.0
Sub-Chapter 4.4			
Fully automated anode effect intervention strategies for PFC emissions	NG	-	4.1a
High and low voltage anode effect description	U	4.2	4.2
PFC emissions during start-up of electrolysis cells	NG	-	4.3
Sub-Chapter 4.8			
Anode effect description (for rare earth metal production by fluoride electrolysis)	NG	-	4.4

CHAPTER 6 ELECTRONICS INDUSTRY EMISSIONS

Sections

This Chapter 6 Volume 3 of the *2019 Refinement* is a complete update 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*.

The *2019 Refinement* of Volume 3 Chapter 6 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 2018 compared to 2006) to calculate default emissions factors for the sector. Also, several methodological refinements are introduced in an attempt to increase accuracy and flexibility, depending on how reporting facilities track gas usage and implement emissions control technologies. The *2019 Refinement* includes six revised methods (Tier 1, 2a, 2b, 2c, 3a, and 3b), compared to four for the *2006 IPCC Guidelines*. The substantial refinements of this Chapter include:

- An expanded basket of gaseous fluorinated compounds (FCs) and fluorinated liquids used or produced as by-products during the manufacture of electronic devices, also including the use and emissions of nitrous oxide (N_2O);
- For the Tier 1 method for gaseous FCs and N_2O, updates to the default emission factors for the semiconductor and display (including LCD, FPD, and other types of display) sub-sectors, and addition of default emission factors for microelectromechanical systems (MEMS);
- For the Tier 2 method for gaseous FCs and N_2O, updates to the default emission factors for the semiconductor and display sub-sectors;
- For the Tier 2 and Tier 3 methods for gaseous FCs and N_2O, new guidance on tracking gas consumption and apportioning use to different process types and wafer sizes;
- For the Tier 2 and Tier 3 methods for gaseous FCs and N_2O, refined approaches to account for emissions control technologies and emissions control technology uptime;
- An update to the Tier 2b method for the semiconductor sub-sector 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 the semiconductor sub-sector that accounts for the size of manufactured wafers in addition to the process type and input gas; this method, without the distinction by substrate size, is also applicable to the display and PV sub-sectors;
- A new section on adapting Tier 2 methods for gaseous FCs and N_2O to account for technological changes, including guidance on (1) when facility-specific measurements should be considered, and (2) the use of hybrid methodologies (e.g. by combining the Tier 2c and Tier 3a methods);
- An update to the 2006 Tier 3 method (now labelled 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;
- For the Tier 1 method for fluorinated liquids, updates to the default emission factors for heat transfer fluid applications in the semiconductor and display sub-sectors, as well as new emission factors for estimating emissions from the packaging, testing, and soldering of packaged semiconductor devices; and
- Corresponding updates to the Completeness, Time Series Consistency, Uncertainty, QA/QC, and Reporting and Documentation sections.

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).

Sections

Section Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Section Number**	***2019 Refinement*** **Section Number**
Electronics Industry Emissions	U, NG	6	6
Introduction	U, NG	6.1	6.1
Gaseous Fluorinated Compounds and Nitrous Oxide	U, NG	6.2.1.1	6.2.1.1
Fluorinated Liquids	U, NG	6.2.1.2	6.2.1.2
Choice of emission factors	U, NG	6.2.2	6.2.2
Gaseous Fluorinated Compounds and Nitrous Oxide	U, NG	6.2.2.1	6.2.2.1
Fluorinated Liquids	U	6.2.2.2	6.2.2.2
Choice of activity data	U	6.2.3	6.2.3
Completeness	U	6.2.4	6.2.4
Developing a consistent time series	U	6.2.5	6.2.5
Uncertainty Assessment	U	6.3	6.3
Emission factor uncertainties	U	6.3.1	6.3.1
Activity data uncertainty	U	6.3.2	6.3.2
Quality Assurance/Quality Control (QA/QC)	U	6.4.1	6.4.1
Reporting and Documentation	U	6.4.2	6.4.2

Equations

Equation Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Equation Number**	***2019 Refinement*** **Equation Number**
Tier 1 Method for estimation of the set of GHG emissions	U	6.1	6.1
Consumption of input gas i	NG	-	6.2
Transfers of Input Gas i	NG	-	6.3
Apportioning of C to Process Types/Sub-types	NG	-	6.4
Emissions of input gas i	U	6.2	6.5
By-product emissions	U	6.3-6.6	6.6
By-product emissions from hydrocarbon fuelled combustion emissions control systems	NG	-	6.7
Emissions reduction impact of emissions control technology for gas i	NG	-	6.8
Emissions reduction impact of emissions control technology for by-product k	NG	-	6.9
Estimate of the mass fraction of gas i emitted from process tools equipped with emission control technologies	NG	-	6.10
Estimate of the mass fraction of by-product k emitted from process tools equipped with emissions control technologies	NG	-	6.11
Uptime of emissions control systems	NG	-	6.12

Equation Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Equation Number**	***2019 Refinement*** **Equation Number**
Emission of input gas i	U	6.7	6.13
Process By-product Emissions from input gas i	U	6.8-6.11	6.14
By-product emissions from combustion emissions control equipment	NG	-	6.15
Emissions reduction impact of emissions control equipment on input gas i	NG	-	6.16
Emissions reduction impact of emissions control equipment on by-product k	NG	-	6.17
Estimate of the fraction of mass of gas i emitted from process p from tools equipped with emissions control equipment	NG	-	6.18
Estimate of the fraction of mass of by-product k emitted from process p from tools equipped with emissions control equipment	NG	-	6.19
Uptime of emissions control systems	NG	-	6.20
Total GHG input gas emitted from stack system during sampling period	NG	-	6.21
Total FC by-product emitted from stack system during sampling period	NG	-	6.22
Gas specific emission factor for input gas	NG	-	6.23
FC by-product specific emissions factor	NG	-	6.24
Annual emissions of input gas i	NG	-	6.25
Annual emissions of FC by-product k	NG	-	6.26
Average emission control system uptime	NG	-	6.27
Tier 1 Method for estimation of total FC emissions from fluorinated liquids	U	6.12	6.28
Tier 2 Method for estimation of FC emissions from fluorinated liquids	U	6.13	6.29

Tables

Table Title	Type of Refinement	*2006 IPCC Guidelines* Table Number	*2019 Refinement* Table Number
Sources and types of GHGs emitted during electronics manufacturing	NG	-	6.1
Refinements and applicability of guidance by electronics industry subsector	NG	-	6.2
Information sources necessary for completing the tiered emission estimating methods for gaseous FCs for electronics manufacturing	U	6.1	6.3
Information sources necessary for completing the tiered emission estimating methods for liquid FCs for electronics manufacturing	NG	-	6.4
Fluorinated liquids commonly used in the electronics industry	NG	-	6.5
Tier1 Gas-specific emission factors for process GHG emissions from electronics manufacturing	U	6.2	6.6
Tier 2a method – default emission factors for GHG emissions from Semiconductor manufacturing and MEMS manufacturing under certain conditions	U	6.3	6.7
Tier 2a & 2b methods – default factors for γ_i and γ_k for semiconductor manufacturing and for MEMS manufacturing under certain conditions	NG	-	6.8
Tier 2b method – default emission factors for GHG emissions from Semiconductor manufacturing and MEMS manufacturing under certain conditions	NG	-	6.9
Tier 2c method (≤200mm) – default emission factors for GHG emissions from semiconductor manufacturing and MEMS manufacturing under certain conditions	NG	-	6.10
Tier 2c method (300mm) – default emission factors for GHG emissions from semiconductor manufacturing and MEMS manufacturing under certain conditions	NG	-	6.11
Tier 2c method – default emission factors for GHG emissions from Display manufacturing	U	6.4	6.12
Tier 2c method – default emission factors for GHG emissions from PV manufacturing	U	6.5	6.13
Methods and procedures for conducting emissions tests for Stack Systems	NG	-	6.14
Maximum field detection limits (FDL) applicable to fluorinated compounds (FC) concentration measurements for Stack Systems	NG	-	6.15
Emissions Control Equipment suitability table for Destruction Removal Efficiency (DRE) of Process GHG Emissions	NG	-	6.16
Tier 2 default DRE parameters for electronics industry process gas emissions reduction technologies	U	6.6	6.17
Tier 1 Default Emission Factors for fluorinated liquids	NG	-	6.18
Estimates of relative uncertainties (percent) of Tier 2b emission factors for semiconductor manufacturing, 95 percent confidence intervals	U	6.9	6.19

Table Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Table Number**	***2019 Refinement*** **Table Number**
Estimates of relative uncertainties (percent) of Tier 2c emission factors for semiconductor manufacturing (≤200 mm), 95 percent confidence intervals	U	6.9	6.20
Estimates of relative uncertainties (percent) of Tier 2c emission factors for semiconductor manufacturing (300 mm), 95 percent confidence intervals	U	6.9	6.21
Tier 2a & 2b methods – estimates of relative uncertainties (percent) for γ_I and γ_K (SEMICONDUCTOR and MEMS manufacturing under certain conditions), 95 percent confidence intervals	NG	-	6.22
Information necessary for full transparency of estimates of emissions from electronics manufacturing	U	6.11	6.23

Figures

Figure Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Figure Number**	***2019 Refinement*** **Figure Number**
Decision tree for estimation of GHG emissions from electronics manufacturing	U	6.1	6.1
Decision tree to determine need for measured emission factors	NG	-	6.2
Decision tree for estimation of emissions from fluorinated liquids loss from electronics manufacturing	U	6.2	6.3
Decision Tree for Process GHG Emission Control System Default Emission Factors	NG	-	6.4

Boxes

Box Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Box Number**	***2019 Refinement*** **Box Number**
Site specific apportioning model verification example	NG	-	6.1
Fluorinated greenhouse gas by-products	NG	-	6.2
The importance and limitations of the default gamma values for calcutating Ai and Ak	NG	-	6.3

CHAPTER 7 EMISSIONS OF FLUORINATED SUBSTITUTES FOR OZONE DEPLETING SUBSTANCES

Sections

- Section 7.1.1 “Chemicals and relevant application areas covered” in the *2006 IPCC Guidelines*: The text about HFCs and Montreal Protocol has been updated. Text and references from the *2006 IPCC Guidelines* are to a large extent retained.
- Section 7.1.2.2 “Choice of method” in the *2006 IPCC Guidelines*: Text updated in order to briefly describe the four new tables with consumption figures for 2015.
- Section 7.5.2.1 “Choice of method” in the *2006 IPCC Guidelines*: New guidance on how to build a refrigeration and air conditioning inventory (Tier 1 and tier 2 emission factor approaches) appears in Boxes 7.2a-c.
- Section 7.5.2.2 “Choice of emission factors” in the *2006 IPCC Guidelines*: Text is updated to describe new information from studies of emission factors. New guidance in terms of examples of national studies on emission rates for stationary refrigeration and air-conditioning systems are found in Annex 7A.1.
- New spreadsheet “Calculation Example for 2F1 (Tier 2)” (MS Excel) was introduced

Section Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Section Number**	***2019 Refinement*** **Section Number**
Chemicals and relevant application areas covered	U	7.1.1	7.1.1
Overview of ODS substitute issues	NR	7.1.2.1	7.1.2.1
Choice of method	U	7.1.2.2	7.1.2.2
Choice of emission factors	NR	7.1.2.3	7.1.2.3
Choice of activity data	NR	7.1.2.4	7.1.2.4
Completeness	NR	7.1.2.5	7.1.2.5
Developing a consistent time series	NR	7.1.2.6	7.1.2.6
Uncertainty Assessment	NR	7.1.3	7.1.3
Quality Assurance/Quality Control (QA/QC), Reporting, and Documentation for all ODS substitutes applications	NR	7.1.4	7.1.4
Choice of method	U	7.5.2.1	7.5.2.1
Choice of emission factors	U,	7.5.2.2	7.5.2.2
Choice of activity data	U	7.5.2.3	7.5.2.3
Applying Tier 2 methods – the example of mobile air conditioning (MAC)	U	7.5.2.4	7.5.2.4
Completeness	NR	7.5.2.5	7.5.2.5
Developing a consistent time series	NR	7.5.2.6	7.5.2.6
Uncertainty Assessment	NR	7.5.3	7.5.3
Quality Assurance/Quality Control (QA/QC), Reporting, and Documentation	NR	7.5.4	7.5.4
Annex 7A.1 to Chapter 7. Examples of national studies on emission rates for stationary refrigeration and air-conditioning systems	NG	-	Annex 7A.1 to Chapter 7
Spreadsheet “Calculation Example for 2F1 (Tier 2)” (MS Excel)	NG	-	Spreadsheet to Chapter 7

Tables

- Tables Table 7.1: Footnote 2 is elaborated, specifying that methodology for estimating emissions for plasma etching is not included in chapter 7. This issue was not in the mandate/TOC.
- Three new tables with consumption figures to address the issue of adding data on the distribution of ODS-substitutes by application, e.g. broadening the set of countries to include developing as well as developed countries. This issue was suggested placed under 7.5.2.3 in the TOC (mandate), but we argue that 7.1.2.2 is the relevant section because it an elaboration related to table 7.3 which is located in section 7.1.2.2:
    - New table 7.3a: Provides information similar to table 7.3 in *2006 IPCC Guidelines* (distribution of HFC use by application area), but for 2015.
    - New table 7.3b: Provides information for 2015 on use of HFCs in RAC by substance and sub-application area in Article 5 Parties.
    - New table 7.3c: Provides information for 2015 on use of HFCs in RAC by substance and sub-application area in non-Article 5 Parties.
    - New table 7.3d: Provides information for 2015 on the share of HFCs used for manufacturing and servicing in RAC.
- Table 7.9: Specifications are made for charge and operating emission factors maritime, railway, busses in sub-application mobile air conditioning to address the issue of updating emission factors by further segregating equipment types.
- Three new tables with emission factors for commercial and industrial refrigeration to address the issue of updating emission factors by further segregating equipment types, regions, and time periods, are presented in Annex 7A.1.

Table Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Table Number**	***2019 Refinement*** **Table Number**
Main application areas for HFCs and PFCs as ODS substitutes	U	7.1	7.1
Distribution of HFC use by application area for 2015	U	7.3	7.3
HFC consumption for RAC in article 5 parties. Per cent of total by substance and sub-application area for 2015	NG	-	7.3a
HFC consumption for RAC in non-article 5 parties. Per cent of total by substance and sub-application area for 2015	NG	-	7.3b
HFC consumption for RAC in article 5 parties and non-article 5 parties. Per cent of total by manufacturing and servicing for 2015	NG	-	7.3c
Default estimates for charge, lifetime and emission factors for refrigeration and air-conditioning systems	U	7.9	7.9
California study for 2008: Emission factors for refrigeration and air conditioning systems	NG	-	7A.1
Japan study for 2008: Emission factors for refrigeration and air conditioning systems	NG	-	7A.2
German study for 2009-2013: Emission factors for refrigeration and air conditioning systems	NG	-	7A.3

Figures

Figure Title	Type of Refinement	*2006 IPCC Guidelines* Figure Number	*2019 Refinement* Figure Number
Decision tree for actual emissions from the refrigeration and air conditioning (RAC) application	NR	7.6	7.6
Example of spreadsheet calculation for Tier 1a/b assessments	NR	7.7	7.7

Equations

Equation Title	Type of Refinement	*2006 IPCC Guidelines* Equation Number	*2019 Refinement* Equation Number
Calculation of net consumption of a chemical in a specific application	NR	7.1	7.1
Calculation of emissions of a chemical from a specific application	NR	7.2a	7.2a
Calculation of emissions of a chemical from an application with banks	NR	7.2b	7.2b
General mass balance equation for Tier 1b	NR	7.3	7.3
Summary emissions equation based on phases of the lifecycle	NR	7.4	7.4
Determination of refrigerant emissions by mass balance	NR	7.9	7.9
Summary of sources of emissions	NR	7.10	7.10
Sources of emissions from management of containers	NR	7.11	7.11
Sources of emissions when charging new equipment	NR	7.12	7.12
Sources of emissions during equipment lifetime	NR	7.13	7.13
Emissions at system end-of-life	NR	7.14	7.14

Boxes

- Three new boxes to address the issue of increased user-friendliness and suggestion of box with “recipe”-style guidance on how to launch the HFC inventory. Location according to suggestion in TOC (mandate):
    - New box 7.2a: Intended to simplify the process of starting an inventory on HFCs, focusing on the larger areas of use and the tier 1 and 2 EF approach.
    - New box 7.2b: Aims at giving an overview of the annual emission estimation process, focusing on the bank of HFCs in equipment in use.
    - New box 7.2c: Provides information on two ways to establish the existing bank of HFCs.
- One new box to address the issue of increased user-friendliness, suggestion of examples regarding the collection of activity data, and the suggestion to further emphasizing the data and literature associated with the Montreal protocol. Location according to suggestion in TOC (mandate):
    - New box 7.3a: List of data sources commonly used for collecting data on HFCS, with a short description of each.
- Box 7.4 in the *2006 IPCC Guidelines* contains misleading information in terms of the emission factors used for MAC. They are outside the default ranges presented in Table 7.9 in 2006 GL due to assumptions on frequent A/C service with high leakage rate. We suggest to reduce the figure to be inside the default ranges provided in the *2006 IPCC Guidelines* Table 7.9 to consistent with the methodologies described.

Box Title	**Type of Refinement**	***2006 IPCC Guidelines* Box Number**	***2019 Refinement* Box Number**
How to build a R/AC inventory in a few simple steps – Tier 1 and 2 emission factor approaches	NG	-	7.2a
The basic elements of an emission inventory for R/AC	NG	-	7.2b
How to build the bank of HFC	NG	-	7.2c
Accounting for imports and exports of refrigerant and equipment	NR	7.3	7.3
Common data sources for the HFC inventory	NG	-	7.3a
Example of the application of a Tier 2a calculation for mobile air conditioning	U	7.4	7.4

CHAPTER 8 OTHER PRODOUCT MANUFACTURE AND USE AND APPENDIX 1 BASIS FOR FUTURE METHODLOGICAL DEVELOPMENT

Sections

- New guidance for waterproofing of electronic circuits has been added to the Section 8.3 “Use of SF_6 and PFCs in other products”.
- New guidance for Textile, carpet, leather and paper fluorinated treatment emissions has been added to the Section 8.3 “Use of SF_6 and PFCs in other products”.
- New Appendix 1 for “Possible Approaches for Estimating FC Emissions from Textile, Carpet, Leather and Paper Industries: Basis for Future Methodological Development” was introduced

Section Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Section Number**	***2019 Refinement*** **Section Number**
Chapter 8			
Introduction	U	8.3.1	8.3.1
Methodological Issues	U	8.3.2	8.3.2
Appendix 1			
Possible Approaches for Estimating Fluorinated Compounds Emissions from Textile, Carpet, Leather and Paper Industries: Basis for Future Methodological Development	NG	-	Appendix 1

Equations

Equation Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Equation Number**	***2019 Refinement*** **Equation Number**
Chapter 8			
Waterproofing of electric circuits	NG	-	8.22a
Appendix 1			
All equations are new	NG	-	1A.1-1A.18

Tables

Table Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Table Number**	***2019 Refinement*** **Table Number**
Chapter 8			
Emission Factor for Waterproofing of Electronic Circuits	NG	-	8.11
Appendix 1			
All tables are new	NG	-	1A.1-1A.4

Boxes

There are no boxes in Chapter 8 of the *2006 IPCC Guidelines* and in Chapter 8 of the *2019 Refinement*

Box Title	**Type of Refinement**	***2006 IPCC Guidelines*** **Box Number**	***2019 Refinement*** **Box Number**
Appendix 1			
All boxes are new	NG	-	1A.1-1A.2

Appendix 1 (New) Possible Approaches for Estimating Fluorinated Compounds Emissions from Textile, Carpet, Leather and Paper Industries: Basis for Future Methodological Development

1A.1 Introduction

Fluorine-based treatment of textiles for waterproofing was introduced in the 1950s (Davies 2014). The first microporous membrane (polytetrafluoroethylene PTFE, also known as Teflon™) was created in 1969 and the first GORE-TEX™ materials appeared on the market in 1976 (Williams 2018). Since then, fluorochemical finishes have been widely used to functionalize fibres for water or oil repellence, soil and stain release, improving textile breathability, softening, dyeing ability, increasing mechanical strength, providing antibacterial and anti-odour finishes, and for fabricating wrinkle-free materials (Choudhury 2017). Such applications are widespread for the production of home textiles, upholstery furniture, protective clothing with signal colour, tent canvas, outdoor wear, medical textiles and work wear such as uniforms and shoes (Lacasse & Baumann 2004; Schindler & Hauser 2004; Singha 2012; Gulrajani 2013; Roshan 2014).

The conventional processes used for increasing the water repellence of fibres use perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkane sulfonic acids (PFSAs), commonly referred to as ‘C8’ chemistry because the precursor molecules contain 8 carbon atoms. Such processes can lead to the formation of Perfluoroalkylated acid through oxidation, and in particular to the environmental release of perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), two chemicals of concern due their persistent and bio-accumulative nature. As a result, the use of C8 fluorinated polymers in textiles, carpet, leather, and paper has been restricted in some regions, and the industry is moving towards shorter chained chemistry (from ‘C8’ to ‘C6’ and ‘C4’). However, the C6 and C4 chemistries have been reported to perform more poorly than the conventional C8 chemistry (Davies 2014), and the C8 chemistry continues to be widely used in regions with large textile production capacities, particularly in developing countries (Fantke et al. 2015). Due to the lower performance of the shorter chained chemistry, alternate methods are being sought for the treatment of textile, carpet, leather and paper. In particular, plasma-based processes have shown promising performance (Davies 2014).

Fluorine-based plasma treatment of textile, carpet, leather, and paper has received increased interest and has been a fertile subject for research and development (R&D) since the early 2000s, in part due to the fact that plasma technologies provide excellent performance and that plasma processes can be tailored to achieve many desirable properties. An increasing number of peer-reviewed papers have been published since 2006, and a growing number of patents have been filed worldwide in the last 5 to 8 years, indicating that technological and industrial developments are occurring rapidly in this emerging field. Several innovative treatment technologies and chemistries are now transitioning to industrial scale use, particularly plasma processing of textiles using gaseous fluorinated compounds (FC) such as CF_4, C_2F_6, C_3F_8, C_4F_8, C_5F_{10}, CHF_3, and SF_6 (Yip et al. 2002; Hochart et al. 2003; Raffaele-Addamo et al. 2003; Davis et al. 2011; Kwong et al. 2013; Ramamoorthy et al. 2013; Davies 2014; Zille et al. 2015; Saxena et al. 2017).

As in the case of the electronics sector, plasma-based processes using fluorinated compounds in the textile industry are expected to result in emissions of unreacted fluorinated compounds and by-products with high global warming potentials (GWPs). However, the extent to which plasma processes have been introduced in volume manufacturing is not clear. Also, the wet application of fluorinated surfactants and fluorine-based polymers commonly used to treat textile, carpet, leather, and paper fibres can result in emissions of volatile fluorinated compounds through evaporative losses and cracking (IPPC 2003; OECD 2004). A list of the most important fluorinated compounds used for plasma-based treatment processes is provided in Table 1Ap.1, and a list of the most important fluorotelomers, fluorocarbons, and fluorosurfactants used for wet applications, as well as their vapour pressures, is provided in Table 1Ap.2. While the magnitude of FC emissions from the textile industry as compared to other sources of fluorinated greenhouse gases (GHGs) is presently unknown, it is clear that the textile industry contributes to some degree to the total amount of fluorinated substances found in the environment (KEMI 2014).

Although several international and national reports refer to the possible off-gas emissions of fluorinated compounds into the atmosphere due to textile treatment, no emission factors appear to be available in the open literature to estimate greenhouse gas emissions from such processes (EPA 1997; Schönberger & Schäfer 2003; MoEU 2012; DEPA 2013; UNIDO et al. 2017). Only one reference about emissions of hydro-fluorocarbons related to the textile industry in the United Kingdom has be found in the literature (Ricardo-AEA 2015). As a consequence, the authors were not able – at the time of writing of this second order draft – to estimate the volume of fluorinated compounds that are used or emitted by the textile, carpet, leather, and paper industries. Nevertheless, FC emissions in this sector could represent a significant new source, due to the large volume of substrates (i.e., product classes) treated and the sheer size and global nature of the industry.

1A.1.1 PLASMA TREATMENT PROCESSES

Plasmas are frequently subdivided into thermal (hot) and non-thermal (cold) plasmas. For thermal plasmas, the temperature of electrons, ions, neutrals and excited species in the plasma state is in equilibrium, ranging from 3,500 ºC to 20,000 ºC. Non-equilibrium (cold) plasmas have electron temperatures that are much higher than the temperature of the ions and neutrals, where the temperature of the plasma is typically in the range of 40 to 250 ºC. Because textiles and polymers cannot withstand the high temperatures used in thermal plasmas, most applications for organic fibres' surface modification use cold plasmas. The majority of plasma-based textile treatment processes for the production of hydrophobic and oleophobic surfaces (but also for some polymer coating, flame retardant and medical antimicrobial fabrics) reported in the technical literature are based on non-thermal plasmas generated at low pressure (between 1 mTorr and 1 Torr) and in few cases at atmospheric pressure. Plasma source designs based on corona discharges, glow discharges, dielectric barrier discharges (DBDs), plasma jet, capacitively or inductively coupled discharges, and RF- or microwave-induced discharges have been studied (Sigurdsson & Shishoo 1997; Tendero et al. 2006; Morent et al. 2008; Sparavigna 2008; Jafari et al. 2013; Vietro et al. 2015; Zille et al. 2015; Gotoh et al. 2017).

Although most plasma processing technologies for textile treatments are still at an emerging stage, several manufacturers have developed pilot- to commercial-scale machinery, and applications for specialized textiles have been or are currently being implemented at industrial scale. Indeed, plasma treatment proves particularly effective for the production of specialty textiles for the medical industry (gowns, masks, protective clothing), the automotive industry (seats, trim, headliners, airbags), the apparel industry (outer and under garments), the filtration industry (air, water filtration) and the flooring industry (carpet fibres) (Saxena et al. 2017). However, the high capital and operational costs of plasma treatment (in particular for low-pressure plasma technologies requiring a closed vacuum system) currently limits the commercial viability of the technique for treating conventional (non-specialized) fabrics. Polymerization of textiles using plasma at atmospheric pressure offers a low-cost and environmentally-friendly alternative, but the technology is still under development (Shishoo 2007; Muthu 2016).

Plasma processes used for the treatment of such materials can be divided into three process types: 1) plasma treatment, 2) plasma etching (or ablation), and 3) plasma polymerization (Roth 2001).

1) Plasma treatment uses inert gases such as Ar, He, N_2, and chemically active molecules such as O_2 or NH_3, as well as fluorinated gases such as CF_4, C_2F_6, C_3F_8, C_4F_8, C_5F_{10}, CHF_3, SF_6, and other (larger size) fluorine-containing molecules such as perfluoroalkyl acrylates (Tendero et al. 2006; Morent et al. 2008; Sparavigna 2008; Jafari et al. 2013; Yim et al. 2013; Vietro et al. 2015; Zille et al. 2015; Gotoh et al. 2017). Plasma treatments can be further separated into two processes sub-types: a) when the plasma-activated gases introduce chemical functionalities or create and deposit free radicals onto the target surface that can be subsequently used to cross-link or surface-graft other molecules to attain specific surface properties (very often more hydrophilic surfaces); or b) when the fabric is first immersed in a fluid of hydrophobic fluorinated pre-polymer with added initiators followed by a plasma treatment leading to the grafting of the pre-polymer on the surface of the fabric.

2) Plasma etching is a process type where the substrate is bombarded with ions from the plasma. Three process sub-types may be defined within the etching process type, depending on whether plasma is used to a) clean, b) sterilize, or c) enhance surface adhesion of the fabrics. For example, dry plasma etching can be accomplished by using CF_4 in a plasma discharge to create active species capable of reacting chemically with the layer to be etched (Sigurdsson & Shishoo 1997).

3) Plasma polymerization is a process type where a monomer in vapour phase such as CF_4, C_2F_6, C_3F_6, or larger fluorinated molecules such as fluorodecylacrylate is converted into reactive fragments to deposit a thin film onto the substrate. Plasma polymerization can be further separated into two process sub-types: a) plasma-induced polymerization is when the polymerization process is a surface-based reaction and, b) plasma-state polymerization is when fragments react in the gas phase to form larger molecules that are then deposited on the substrate (Morent et al. 2008).

For all process types and sub-types, it is highly improbable that all input chemicals are fully consumed in the process (IPCC 2006). Further, the plasma decomposition of input chemicals such as C_2F_6, C_3F_8, and larger chain fluorinated molecules is likely to result in the production of byproducts such as CF_4, C_2F_6, CHF_3 and other gases. Therefore, plasma-based fluorinated treatment of textile, carpet, leather, or paper is expected to lead to emissions of FC greenhouse gases. It should be noted that the potential for plasma-based polymerization processes to emit large amounts of FCs is likely lower than for the plasma treatment and plasma etching process types because, in the case of polymerization, the input FC chemicals are meant to react and form solid byproducts on the substrate as opposed to just treat or etch its surface. However, it should also be mentioned that plasma-based polymerization is more effective than many conventional wet-based chemistries, and that such characteristics may contribute to shifting emissions towards high-GWP gases. Finally, the extent to which reactor cleaning processes (to remove the deposits that build on the chamber walls after multiple depositions) may contribute to GHG emissions is unclear at the time of writing of the Second Order Draft of the *2019 Refinement*, and comments are sought on this particular issue.

1A.1.2 WET TREATMENT PROCESSES

Wet treatment processes include several application techniques but about 80per cent of the processes use the pad-dry-cure method, where the dry fabric is immersed in the finishing liquor and then squeezed between rollers before being dried and finally cured, usually at a temperature of between 150 and 180 ºC (Roshan 2014). Other techniques include vacuum extraction, spray applications, foam finishing, coating, and lamination.

Side-chain fluorinated polymers primarily based on fluorotelomer acrylates, fluorotelomer methacrylates or per-fluoroalkane sulfonamidoethanols characterize the chemical structure of the fluorine-based surfactants and polymers used for the above-described applications. Unfortunately, the environmental and health characteristics of the new short-chain chemistry and associated processes are poorly described in the scientific literature. Although some reports refer to possible emissions of FCs in the atmosphere due to textile-wet coating, no data or estimations of emissions are provided (IPPC 2003; Ellis et al. 2004; OECD 2004; Dumoulin et al. 2005; Prevedouros et al. 2006; Barber et al. 2007; Jahnke et al. 2007; FOEN 2009; Young 2010; DEPA 2015; UNEP 2017). Data on the volatile PFASs that are emitted immediately after the production of textiles, the type of PFASs that can be formed by hydrolysis of the perfluorinated polymer side chains during use, washing and degradation of the fabrics is also seemingly missing.

Importantly, it must be considered that FC products are likely to be released to the air during their industrial application to fibres, particularly during the curing phase of the treatment. It has been shown that, during the drying and curing phases, off-gas emissions can be produced by the volatility of the active substances themselves as well as by their constituents, which can contain on average 1per cent of unreacted and unbound residuals such as monomers, fluorotelomer alcohols (sometimes up to 6-8per cent of the dry weight) and perfluoroalkyl carboxylic acids (Heydebreck et al. 2016). Overall, it can be expected that the magnitude of emissions will depend on the drying or curing temperature, the substrate material, and the reagents' volatility, concentrations and reactivity (European Commission 2003). To complicate the matter, there is a wide range of different application methods (e.g. padding, spray, foaming, coating, lamination, etc.), different vapour pressure of input chemicals, and different temperature and time of drying and curing steps of the treated substrates. For example, some leather stain resistant finishing agents are applied by spray and dried at room temperature while most of the textile finishing require a drying (110-130ºC) and curing (150-180 ºC) steps (Williams 2018). Carpet products may be cured at a lower temperature of 110 ºC while other products may be treated for 2 minutes at 170ºC or for 30 seconds at 190ºC (e.g. cotton). Moreover, some carpet treatments require a curing step for water and oil repellence when using FCs deposition, but on the contrary no curing is required for some type of solvent soluble fluorinated soil release finishing agents for garments, upholstery and carpets (Goswami 2017). However, the latter kind of treatments has lower durability than water-based FCs because of the lack of fixation by crosslinking (Schindler & Hauser 2004). Generally, the higher the curing temperature, the shorter is the curing time in order to avoid yellowing of the fabric. Residuals and impurities may also be released directly from the products into the environment through volatilization, and FC emissions may result from the cracking of input chemicals. Thus, presumptively, emissions of high-GWP gases from wet-based fluorinated treatment of textile, leather, and paper fibres may represent a substantial source. However, the potential climate impact of such processes and substances does not appear to have been characterized in the literature, which typically focuses on formaldehyde, total organic carbon release and on a very limited selection of well-known long-chain PFASs such as perfluorooctanesulfonate (PFOS), perfluorooctanoic acid (PFOA) and their precursors (Wang et al. 2017).

TABLE 1AP.1
LIST OF MOST IMPORTANT INPUT CHEMICAL MONOMERS USED IN PLASMA TREATMENT OF TEXTILES

Atmospheric plasma[1]	**Low pressure plasma**[2]
$C_{11}H_7F_{13}O_2$	CF_4 (PFC-14)
$C_{13}H_7F_{17}O_2/C_{15}H_7F_{21}O_2$	C_2F_4 (PFC-1114)
Unidyne TG-571®	C_3F_6 (Perfluorocyclopropane)
CF_4 (PFC-14)	C_2F_6 (PFC-116)
CHF_2CF_3 (HFC-125)	C_3F_8 (PFC-218)
CHF_3 (HFC-23)	C_4F_{10} (PFC-31-10)
C_3F_6 (Perfluorocyclopropane)	C_6F_{14} (PFC-51-14)
C_2F_6 (PFC-116)	C_4F_8 (PFC-318)
$C_8F_{17}CH_2CH_2OCOCH=CH_2$	CHF_2CF_3 (HFC-125)
C_3F_8 (PFC-218)	SF_6 (Sulfur hexafluoride)
$C_{13}H_7F_{17}O_2$	CF_3SO_3H (co-monomer)
SF_6 (Sulfur hexafluoride)	C_2ClF_3 (co-monomer)
$H_2C=CHCO_2CH_2CH_2(CF_2)_7CF_3$	C_6F_6 (co-monomer)
$C_6H_{13}F_3O_3Si$ (FAS-3)	HC_6F_5 (co-monomer)
$C_6F_5Si(OC_2H_5)_3$ (FAS-5)	$CF_3(CF_2)_7CH=CH_2$
$C_{13}H_{13}F_{17}O_3Si$ (FAS-17)	1,1,2,2, tetrahydroperfluorodecyl acrylate (AC8)

Note:

Despite the fact that some chemicals have been defined using their common names, most of the listed chemicals represent chemical families, co-monomers or commercial products. Please refer to the IUPAC name for the other chemicals.

Sources:

[1] Yim et al. 2013; Gotoh et al. 2017; Tendero et al. 2006; Zille et al. 2015; Sparavigna 2008; Morent et al. 2008

[2] Vietro et al. 2015; Zille et al. 2015; Sparavigna 2008; Morent et al. 2008; Jafari et al. 2013; Hochart et al. 2003; Hegemann 2006

TABLE 1AP.2
LIST OF MOST IMPORTANT INPUT CHEMICALS USED IN WET TREATMENT PROCESS, AND THEIR VAPOUR PRESSURE

Chemical name	**Vapour pressure (mm Hg @ 25°C)**[1]
Tetrafluoroethylene	24500
Chlorotrifluoroethylene	4590
Vinylidene fluoride	30000
Vinyl fluoride	19800
Hexafluoropropene	4900
Perfluoromethylvinyl ether	765
Perfluoropropylvinyl ether	534
Perfluorooctane sulfonic acid (PFOS)	0.002
Perfluorobutane sulfonic acid (PFBS)	0.027
n-methyl perfluorobutane sulfonamidoethanol (Me-FBSE)	0.05
3-(Perfluorobutyl)propanol (PFBP)	0.7
Ethyl perfluorooctanoate (EPFO)	0.97-1
Perfluoro-3,6-dioxaheptanoic acid (PDHA)	1.06
Fluorotelomer alcohol 10:2 FTOH	1.1 - 0.001
PFOA isomers	1.26 - 2.04
Perfluorooctane sulfonyl fluoride (POSF)	5.75
Fluorotelomer alcohol 8:2 FTOH	1.9 - 0.03
Perfluorohexanoic acid (PFHxA)	1.98
Heptafluorobutyric acid - C4HF7O (PFBA)	10
Perfluorobutanoic acid (PFBA)	10 (20ºC)
Fluorotelomer alcohol 4:2 FTOH	12.5 - 1.6
1,1,2,2-Tetrafluoroethyl methyl ether	1280
Perfluorobutyl iodide	158
Polyfluorinated fluorotelomer iodides (6:2 FTI)	2.9
C_6F_{14} (PFC-51-14)	232
$C_5F_{11}NO$	274
C_8F_{18}	29
(perfluorooctyl)ethylene (PFOE)[1]	3.6
(Perfluorohexyl)ethylene	43.8
1H,1H,2H-Perfluoro-1-decene	6.36
Fluorotelomer alcohol 6:2 FTOH	6.6 - 0.1
C_5F_{12} (PFC-41-12)	610
C_7F_{16}	79

Notes:
- Please note that even though most of the PFOS and PFOA compounds have very low vapour pressure at 25 ºC, they are cured during applications at temperatures of between 150 and 180 ºC.
- Despite the fact that some chemicals have been defined using their common names most of the listed chemicals represent chemical families. Please refer to the IUPAC name for the other chemicals.

Sources:
[1] Schindler et al. 2013; National Institutes of Health; Nielsen 2012; Ruan et al. 2013; Harrad 2001

1A.2 Methodological issues

1A.2.1 CHOICE OF METHOD

The choice of method will eventually depend on the availability of measured emission factors from which default factors might be derived. The bibliographic research conducted as of the date of this Second Order Draft does not indicate that representative FC emissions data can be obtained from the textile, carpet, leather, or paper industries to derive default emission factors for Tier 1 or Tier 2 methods. Nevertheless, the authors propose herewith a four-tiered methodological framework (Tier 1, Tier 2a, Tier 2b, and Tier 3) to account for emissions from this sector. At this point, because no Tier 1 or Tier 2 default factors are available, only the Tier 3 method is practicable, using equipment-specific, process-specific, or site-specific measured emission factors. Distinct methods are provided for plasma-based processes and for wet-based processes. This Appendix provides a basis for future methodological development rather than complete guidance.

The inventory methods proposed for plasma-based processes are analogous to those used in the electronics industry due to the similarity of the processes, and include four tiered methods (Tier 1, 2a, 2b, 3). The Tier 1 method does not require gas consumption data and provides an estimate of emissions based on default (industry average) emission factors expressed in mass of FC emitted per unit area of substrate treated. The Tier 2a and 2b methods require FC consumption data at the site or national level and are based on process gas-specific default emission factors expressed in terms of mass of FC emitted per mass of FC consumed (including both emissions of unreacted FC and emissions of all FC by-products formed during the process). For plasma processes, the difference between the Tier 2a and 2b methods is that the Tier 2b method differentiates emission factors by type of plasma process (plasma treatment, plasma etching, and plasma polymerization) and/or class of products manufactured (textiles, leather, paper, etc.), while the Tier 2a method does not. A Tier 3 method would use the same equations as the Tier 2b method, but would use measured emission factors (equipment-specific, process-specific, substrate-specific, or site-specific) instead of default emission factors.

For wet-based processes, a Tier 1 approach is proposed as a framework to estimate FC emissions based on the mass of substrate treated, a method, which would therefore not require data on the consumption of input chemicals. Two Tier 2 methods (Tier 2a and 2b) are also proposed as frameworks to report emissions based on default FC emission factors allowing to correlate the mass of wet input chemicals consumed to the mass of volatile by-products formed during the processes. The difference between the Tier 2a and 2b methods for wet processes is that the Tier 2b method would distinguish emission factors by process and/or substrate type (class of products) (see further discussion below), while the Tier 2a method would not. Finally, a Tier 3 method applicable to wet processes would use the same equations as the Tier 2b method, but would use measured emission factors (equipment-specific, process-specific, or site-specific) instead of default emission factors.

Generally, the higher tiered methods will be more accurate than the lowered tiered ones, and using equipment-specific, process-specific, or site-specific emission factors will improve accuracy and greatly reduce the uncertainty of emissions estimates. The accuracy of the methods using default emission factors 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 the consumption of input chemicals, and in reporting the abatement efficiency and the uptime of emissions control systems. With respect to uncertainty, the confidence level of a particular emissions estimate will likely be principally driven by the uncertainty of the default emission factors.

1A.2.1.1 PLASMA TREATMENT PROCESSES

Table 1Ap.3 depicts the information sources necessary for completing the tiered methods for estimating emissions from plasma treatment processes. This information is preliminary and likely to evolve as the definitions of the various methods are refined. At the time of writing of this Second Order Draft, no information about emission factors could be obtained for plasma treatments from the textile, carpet, leather, or paper industries to derive default emission factors for the Tier 1, Tier 2a, or Tier 2b methods. Thus, currently, the only practicable means to estimate emissions from this sector is the use of the Tier 3 method. Nevertheless, when a statistically-significant number of representative experimental emission factors becomes available, preliminary recommendations are provided for estimating default emission factors and for choosing the most appropriate Tier 1, Tier 2a, or Tier 2b methods.

Depending on the method used, data based on production capacity (Tier 1), or data about input chemicals consumption, use rate, by-products formation rates, and the effectiveness of emissions control measures (Tier 2a, 2b, 3) will be required for the calculation of emissions. For each variable, depending on the tiered method, an industry default value (D) may be used, measured (Me), or modelled (Mo) to account for site-specific values. With respect to accounting for emissions control technologies, the approach provided here is analogous to the method provided for the electronics industry. For more information, please refer to Chapter 6 “Electronic Industry Emissions”.

While continuous (in-situ) emissions monitoring may be technically feasible, it is unclear whether such an approach could be an economically viable method to estimate emissions from the textile, carpet, leather, or paper industry. One alternate approach would be to measure emission factors during the development of new plasma processes when parameters such as input gas flows, chamber pressure, processing time, plasma power, etc. are adjusted for particular treatment needs or for manufacturing a particular product. Please see Box 1Ap.1 for guidance on the analytical methods that can be used for measuring emission factors.

Another approach would be for facilities to 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 (see, e.g., the Tier 3b method developed for Chapter 6 “Electronic Industry Emissions”). It is very important to note that emission factors (i.e. input gas utilization efficiencies and by-product formation rates) can be strongly affected by changes in process variables (e.g. type of textile substrate material, pressure, temperature, plasma power, FC gas flow, processing time, etc.) and by the design of the process reactors. Thus, emission factors can substantially fluctuate from one tool manufacturer to another and for a recipe ‘tuned’ for a particular purpose or product.

TABLE 1AP.3
INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR PLASMA TREATMENT OF TEXTILE, LEATHER, AND PAPER

Data		Tier 1	Tier 2		Tier 3
			2a	2b	
Process Gas Entering Tools	$FC_{i,}$ = consumption of gas *i*		Me/Mo		
	$FC_{i,p}$ = consumption of gas *i* for process *p*.[a]			Me/Mo	Me/Mo
	h_i = Fraction of gas remaining in shipping container after use (heel) for gas *i*.		D/Me	D/Me	Me
Process Gas Reactions and Conversion in Tools	U_i = Use rate (fraction destroyed or transformed) for each gas *i*.		D		
	$U_{i,p}$ = Use rate (fraction destroyed or transformed) for each gas *i* and process *p*.[a]			D	Me
	$B_{k,i,}$ = Emission factor for by-product *k* for input gas *i*.		D		
	$B_{k,i,p}$ = Emission factor for by-product *k* for input gas *i* and process *p*.[a]			D	Me
Downstream FC Emission Control	$a_{i,}$ = Fraction of gas *i* volume used in processes with certified FC emission control technology		Me		
	$a_{i,p,}$ = Fraction of gas *i* volume fed into processes *p* with certified FC emission control technology			Me[a]	Me[a]
	d_i = Destruction Removal Efficiency (DRE) for gas *i*		D/Me		
	$d_{i,p}$ = Destruction Removal Efficiency (DRE) for gas *i* for process *p*			D/Me[a]	D/Me[a]
	UT = Average uptime factor of all abatement systems connected to process tools		Me		
	UT_p = Average uptime factor of all abatement systems connected to process tools running process type *p*			Me[a]	Me[a]
Annual Production Capacity	EF_i = emission factor for FC gas i	D			
	C_u = fraction of annual plant production capacity utilization	Me			
	C_d = annual manufacturing design capacity	Me			

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 plasma process type (Tier 2b) or a site-specific process (Tier 3).

TIER 1 METHOD FOR PLASMA TREATMENT PROCESSES – DEFAULT

The Tier 1 method is the least accurate estimation method and should be used only in cases where site-specific data on the consumption of input chemicals are not available. The Tier 1 method, unlike the Tier 2a, 2b or Tier 3 methods, is designed to give an aggregated estimate of FC emissions, although its methodology appears to produce gas-specific emissions. As envisioned, Tier 1 estimates would be made simultaneously for all (or for the most important) gases listed in Table 1Ap.1 and could only be used if reported as a complete set.

As proposed, the Tier 1 calculation relies on a fixed set of generic emissions factors and does not account for differences among process types (plasma treatment, etching, or polymerization), individual processes or manufacturing tools. However, the members of the set would likely differ depending on the surface area of textile, carpet, leather, or paper products being manufactured. Each member of a set, which is a gas-specific emission factor, would express average emissions per unit of substrate area (textile, carpet, leather, paper) produced during manufacture.

In using Tier 1, inventory compilers should not modify, in any way, the set of FCs assumed to represent average emissions. Further, as is common practice for IPCC methods, the Tier 1 method does not allow accounting for the use of emissions control technologies, and 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_4 to estimate the emissions of CF_4 from textiles etching and combine it with the results of other FC gases from a Tier 2 or Tier 3 method. The formula used to calculate Tier 1 emissions is shown in Equation 1Ap.1.

EQUATION 1AP.1
TIER 1 METHOD FOR ESTIMATION OF THE SET OF FC EMISSIONS

$$\left\{FC_i\right\}_n = \left\{EF_i \bullet C_u \bullet C_d\right\}_n \qquad (i = 1, \ldots, n)$$

Where:

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

Note: $\{\ \}_n$ denotes the set for each class of products (e.g. textile, carpet, leather, or paper) and *n* denotes the number of gases included in each set. 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^2

C_u = fraction of annual plant production capacity utilization, fraction

C_d = annual manufacturing design capacity, m^2 of substrate processed

TIER 2A METHOD FOR PLASMA TREATMENT PROCESSES – PROCESS CHEMICAL-SPECIFIC PARAMETERS

The Tier 2a method uses industry-wide default values for the fraction of input chemicals used in the plasma manufacturing process (U_i), the fraction of input chemicals *i* converted into FC by-products *k* during the process ($B_{k,i}$), and the fraction of FC destroyed by the emissions control technology (D_i). The Tier 2a method also calculates emissions for each input chemical used on the basis of site-specific data on chemicals consumption and emissions control technologies. 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. For the 'heel' or fraction of the purchased gas remaining in the shipping container after use (h_i), facilities may use default or site-specific values.[1]

Unlike the Tier 2b and Tier 3 methods that are explained later in this section, the Tier 2a method does not distinguish between process types (treatment, etching, or polymerization) or site-specific processes. However,

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[1] For an example of how site-specific heel factors can be developed, please see Chapter 6 Volume 3 of the *2019 Refinement*.

the Tier 2a default emission factors are formed separately for each input chemical, which, unlike the Tier 1 method, allows to account for the actual mix of input chemicals used at a particular manufacturing site.

Total Tier 2a emissions are equal to the sum of emissions from all unreacted fluorinated chemicals i used in the production process (E_i) plus emissions of all by-products k (BPE_k) resulting from the conversion of all input chemicals used during production, as calculated using equations 1Ap.2, and 1Ap.3 below.

EQUATION 1AP.2
TIER 2A ESTIMATION OF EMISSIONS OF UNREACTED INPUT CHEMICALS

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

Where:

E_i = emissions of unreacted input chemical i, kg

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

FC_i = consumption of input chemical i, kg

U_i = use rate of input chemical i (fraction destroyed or transformed in process), fraction

D_i = Overall reduction of gas i emissions, fraction, calculated per equation 1Ap.4

EQUATION 1AP.3
TIER 2A ESTIMATION OF BY-PRODUCT EMISSIONS

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

Where:

BPE_k = emissions of by-product *k* generated from the conversion of all input chemicals *i*, kg

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

FC_i = consumption of input chemical *i*, kg

$B_{k,i}$ = emission factor, kg of by-product *k* created per kg of input chemical *i* used

D_k = overall reduction of gas k by-product emissions, fraction, calculated per equation 1Ap.4 (replacing i by k indexes)

EQUATION 1AP.4
EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL TECHNOLOGY

$$D_i = a_i \bullet d_i \bullet UT$$

Where:

D_i = overall reduction of chemical i emissions, fraction

a_i = fraction of chemical *i* volume used in processes with emission control technologies (site-specific), fraction

d_i = Destruction Removal Efficiency (DRE) for chemical i, fraction

UT = average uptime of all abatement systems, fraction, calculated per Equation 1Ap.5

EQUATION 1AP.5
UPTIME OF EMISSION CONTROL SYSTEM

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

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. UT may be set to 1 if suitable backup abatement or interlocking with the process tool is implemented for each abatement system[2]

n = abatement system

TIER 2B METHOD FOR PLASMA TREATMENT PROCESSES – PROCESS TYPE-SPECIFIC PARAMETERS

The Tier 2b method is similar to the Tier 2a approach in the sense that it is based on chemical-specific default emission factors, but the Tier 2b factors also account for the type of plasma process and/or class of products (i.e. textile, carpet, leather, paper) used for production processes 'p'. Thus, the Tier 2b approach is expected to be more accurate than the Tier 2a one because the Tier 2b method reflects the mix of processes or classes of products used in a particular manufacturing facility. Also, the Tier 2b method allows to account for the trend where some chemicals tend to be used predominantly in particular process types and class of products manufactured. The Tier 2b method uses industry-wide default values for the fraction of input chemicals i used in plasma production process p ($U_{i,p}$), the fraction of input chemicals i converted into FC by-products k during process p ($B_{k,i,p}$), and the fraction of FC destroyed by the emissions control technology connected to tools using production process p ($D_{i,p}$). For the 'heel' or fraction of the purchased gas remaining in the shipping container after use (h_i), facilities may use default or site-specific values.[3]

Although the Tier 2b method is preferred over the Tier 2a method because process- or product-type specific emission factors are more accurate, it should be noted that the Tier 2b method presents increased complexity because the consumption of input chemicals must be allocated to each production process p. Thus, in the case where the consumption of input chemicals cannot directly be measured for each production process p, a gas consumption allocation model must be devised for applying the method,[4] and inventory compilers should consider the trade-off of using more accurate process-specific emission factors versus introducing errors in the Tier 2b estimate, due to uncertainties in the allocation model.

Total Tier 2b emissions are equal to the sum of emissions from all unreacted fluorinated chemicals i used in all production processes p (E_i) plus emissions of all by-products k resulting from the conversion of all input chemicals used during all production processes p (BPE_k), as calculated using equations 1AP.6, and 1AP.7 below.

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[2] 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.

[3] For an example of how site-specific heel factors can be developed, please see Chapter 6 Volume 3 of the *2019 Refinement*.

[4] For an example of how site-specific gas consumption allocation models can be developed, please see Chapter 6 Volume 3 of the *2019 Refinement*.

EQUATION 1AP.6
TIER 2B ESTIMATION OF EMISSIONS OF UNREACTED INPUT CHEMICALS

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

Where:

E_i = emissions of unreacted input chemical i, kg

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

$FC_{i,p}$ = consumption of input chemical i for production process p, kg

$U_{i,p}$ = use rate of input chemical i (fraction destroyed or transformed in production process p), fraction

$D_{i,p}$ = overall reduction of gas i emissions from tools using production process p, fraction, calculated per equation 1Ap.8

EQUATION 1AP.7
TIER 2B ESTIMATION OF BY-PRODUCT EMISSIONS

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

Where:

BPE_k = emissions of by-product k generated from the conversion of all input chemicals i used 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 of by-product k created per kg of input chemical i used for production process p

$FC_{i,p}$ = consumption of input chemical i for production process p, kg

$D_{k,p}$ = overall reduction of gas k by-product emissions from tools using production process p, fraction, calculated per equation 1Ap.8 (replacing i by k indexes)

EQUATION 1AP.8
EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL TECHNOLOGY

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

Where:

$D_{i,p}$ = overall reduction of chemical i emissions from production process p, fraction

$a_{i,p}$ = fraction of chemical i volume fed into production process p with emission control technologies (site-specific), fraction

$d_{i,p}$ = Destruction Removal Efficiency (DRE) for chemical i and production process p, fraction

UT_p = average uptime of all abatement systems connected to tools using production process p, fraction, calculated per Equation 1Ap.9

EQUATION 1AP.9
UPTIME OF EMISSION 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 production process p, fraction

$Td_{n,p}$ = The total time, in minutes, that abatement system n connected to process tool(s) running production process 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 production process p in operation. UT may be set to 1 if suitable backup abatement or interlocking with the process tool is implemented for each abatement system[5]

n = abatement system

TIER 3 METHOD FOR PLASMA TREATMENT PROCESSES – SITE-SPECIFIC PARAMETERS

The Tier 3 method uses the same set of equations (equations 1Ap.6 to 1Ap.9) as the Tier 2b method. However, when using the Tier 3 method, inventory compilers need to interpret ‘p’ in these equations as a specific production process using a specific ‘recipe’. A recipe corresponds to a particular combination of input gases under specific conditions of process duration, temperature, pressure, flow, plasma power, class or product, and other relevant process parameters adjusted to achieve a particular result (i.e. water or stain resistance, increased mechanical strength, etching medical polyamide, etc.) on a specific process reactor. It is very important to note that emission factors such as input gas utilisation efficiencies and by-product formation rates can be strongly affected by changes in process parameters (duration, temperature, pressure, flow, plasma power, reactor design, etc.).

When using the Tier 3 method, the (1-U) and BPE emission factors in Equations 1.Ap.6 and 1.Ap.7 should be measured for specific processes recipes. However, a centreline process recipe may be used to establish Tier 3 emission factors for sets of ‘similar’ recipes. Recipes can be 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 process type (plasma treatment, plasma etching, and plasma polymerization), product, process tool, and input process gases are the same. When using the concept of ‘similarity’, inventory compilers should be able to reasonably demonstrate that emissions estimates are not biased (i.e. systematically over- or under-estimated) when using centreline process recipe(s) emission factors.

Once default Tier 2a or Tier 2b emission factors will be developed, the Tier 3 method should be used by manufacturing plants whose processes and recipes depart significantly from industry-wide patterns of use (e.g. for facilities using an input chemical primarily in plasma etching while others primarily use it in plasma polymerization), or by manufacturing plants that may have developed specific processes whose characteristics may result in a significantly lower or higher utilization of input chemicals or formation of byproducts. Further, if

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[5] 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.

default Tier 2 emission factors are not available for a particular process or input chemical, manufacturing facilities should measure their site-specific emission factors and use the Tier 3 method.

It should also be noted that Tier 3 emission factors could be combined with Tier 2a or 2b default emission factors (once available) to use a hybrid method. 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. Indeed, higher accuracy might be achieved by using the Tier 3 method for specific input chemicals or site-specific processes. However, inventory compilers should not combine the Tier 1 method with any other method.

The Tier 3 method is not outlined further in this Appendix, but inventory compilers should refer to the Box 1Ap.1 on specific technologies for the measurement of FC emissions in order to develop facility- or country-specific emission factors as a resource for implementing the Tier 3 method. Also, measurement methods developed for the electronics industry could be used as a basis for measuring emission factors from plasma-based finishing processes in the textile, carpet, leather, and paper industries (Benaway et al. 2014).

BOX 1AP.1

ANALYTICAL METHODS FOR MEASURING FC EMISSIONS

Fourier transform infrared spectroscopy (FTIR) is the currently preferred option due to part per billion (ppb) sensitivity, portability, ability to enable near-real-time measurements, reprocess historical data, and provide multi-component analysis and resistance to magnetic fields. However, FTIRs are generally considered to be higher-cost systems, requiring significant upkeep during sampling campaigns. Depending on the absorptivity and concentration of the FC gases to be detected, FTIR gas cells with long path lengths (meters) might be required to reach suitable detection levels (Espinoza-Nava et al. 2016).

Gas chromatography followed by mass spectrometry (GC/MS) can provide a near real time measurement of FC, as well as several other gas sample components if desired. The instrument must be calibrated in place, prior to the start of FC monitoring. If GC/MS measurement is not possible on a continuous basis this technology allows for sample collection that can be transported to a laboratory for analysis, directly in sample bags or by desorbing components after time average sampling onto sorbent columns. Using samples in bags or metal canisters, detection limits of 0.05 ppmv and 0.04 ppmv for CF_4 and C_2F_6, respectively, can be achieved. Using the sorbent columns detection limits of 9 ppbv for CF_4 and 0.6 ppbv for C_2F_6 have been validated (EPA & IAI 2008). Detection limits can be improved with modification of desorption parameters if desired. Method Detection Limit (MDL) from 0.001 to 3.5 pg.m^{-3} were reported for indoor and outdoor determination of several volatile perfluorinated compounds with the use of high volume samples and efficient enrichment steps (Trojanowicz & Koc 2013).

1A.2.1.2 WET TREATMENT PROCESSES

Table 1Ap.4 depicts the information sources necessary for completing the tiered methods for estimating emissions from wet-based treatment of textiles, carpet, leather, and paper. This information is preliminary and likely to evolve, as the definitions of the various methods are refined. At the time of writing of this Second Order Draft, no information about emission factors could be obtained for wet-based treatments from the textile, carpet, leather, or paper industries to derive default emission factors for the Tier 1, Tier 2a, or Tier 2b methods. Thus, currently, the only practicable means to estimate emissions from this sector is the use of the Tier 3 method. Nevertheless, when a statistically-significant number of representative experimental emission factors become available, preliminary recommendations are provided for estimating default emission factors and for choosing the most appropriate Tier 1, Tier 2a, or Tier 2b methods.

Depending on the method used, data based on production capacity (Tier 1), or data about input chemicals consumption, use rate, by-products formation rates, and the effectiveness of emissions control measures (Tier 2a, 2b, 3) will be required for the calculation of emissions. For each variable, depending on the method, an industry default value (D) may be used, modelled (Mo), or measured (Me) to account for site-specific values. As mentioned earlier, emissions of greenhouse gases from wet treatment processes may result from evaporative losses of the input liquid chemicals and from the formation of volatile fluorinated compounds through chemical reactions during the processes, all of which can be considered volatile by-product emissions resulting from the use of the liquid input chemicals. Thus, unlike for plasma-based processes, the equations for the Tier 2a, 2b and

Tier 3 methods for wet treatment processes do not take into account the utilization efficiency of the input liquid chemicals – most of which remain on the substrate as a coating (in a solid state), and only volatile by-product emission factors are necessary to account for all emissions (EV_i and $B_{k,i}$ for the Tier 2a and $EV_{i,p}$ and $B_{k,i,p}$ for the Tier 2b and Tier 3 methods). Also, the equations for wet treatment processes do not include a heel factor (fraction of gas remaining in the shipping container in the methods used for plasma-based processes). The emission factors for textile industry will be calculated for the emission potential of auxiliaries to the produced amount of textile in kg.[6]

While continuous (in-situ) emissions monitoring may be technically feasible, it is unclear whether such approach could be an economically viable method to estimate emissions from the textile, carpet, leather, or paper industry. One alternate approach would be to measure emission factors during the development of new wet-based processes when parameters such as coating velocity, liquid ratio, processing time, curing and dying temperatures, etc. are adjusted for particular treatment needs or for a particular product. Please see Box 1Ap.1 for guidance on the analytical methods than can be used for measuring emission factors.

Another approach would be for facilities to 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. It is very important to note that emission factors (i.e. input liquid utilization efficiencies and by-product formation rates) can be strongly affected by changes in process variables (e.g. type of textile substrate material, curing temperature, liquid ratio, used chemical, processing time, etc.) and by the design of the process equipment. Thus, emission factors can substantially fluctuate from one tool manufacturer to another and for a recipe ‘tuned’ for a particular purpose or product.

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[6] Textile auxiliaries are defined as chemicals of formulated chemical products which enable a processing operation in preparation, dyeing, printing or finishing to be carried out more effectively or which is essential if a given effect is to be obtained.

TABLE 1AP.4
INFORMATION SOURCES NECESSARY FOR COMPLETING THE TIERED EMISSIONS ESTIMATING METHODS FOR WET-BASED TREATMENT OF TEXTILE, CARPET, LEATHER, AND PAPER

Data		Tier 1	Tier 2		Tier 3
			2a	2b	
Consumption of liquid input chemicals	C_i = liquor concentration for input chemical *i* (fraction, kg of input chemical i per kg of liquor).		Me/Mo		
	LP_i = liquor pick-up for input chemical *i* (fraction, kg of liquor containing input chemical i per kg of textile substrate).		Me/Mo		
	$C_{i,p}$= liquor concentration for input chemical *i* and process *p*, (fraction, kg of input chemical i per kg of liquor for process *p*).			Me/Mo	Me/Mo
	$LP_{i,p}$ = liquor pick-up for input chemical *i* and process *p*, (fraction, kg of input chemical i per kg of liquor for process *p*).			Me/Mo	Me/Mo
Formation of volatile by-products	$B_{k,i,}$ = substance emission factor for volatile by-product *k* for input chemical *i* (fraction, kg of volatile by-product formed per kg of input chemical consumed)		D		
	$B_{k,i,p}$ = substance emission factor for volatile by-product *k* for input chemical *i* and process *p* (fraction, kg of volatile by-product formed per kg of input chemical consumed for process *p*)			D[a]	Me[a]
Downstream FC Emission Control	$a_{k,}$ = fraction of by-product *k* produced in processes with certified FC emission control technology		Me		
	$a_{k,p,}$ = fraction of by-product *k* produced from processes *p* with certified FC emission control technology			Me[a]	Me[a]
	d_k = Destruction Removal Efficiency (DRE) for by-product *k* (per cent)		D/Me		
	$d_{k,p}$ = Destruction Removal Efficiency (DRE) for by-product *k* for process *p* (%)			D/Me[a]	D/Me[a]
	UT = Average uptime factor of all abatement systems connected to process tools		Me		
	UT_p = Average uptime factor of all abatement systems connected to process tools running process type *p*			Me[a]	Me[a]
Annual Production Capacity	EF_k = emission factor for volatile by-product k (kg of volatile by-product formed per kg of substrate produced)	D			
	C_u = fraction of annual plant production capacity utilization	Me			
	C_d = annual manufacturing design capacity (kg of substrate processed)	Me			

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

[a] {For the Tier 2b method ‘*p*’ is to be interpreted as a wet process type and/or a substrate type (see further discussion below)}. For the Tier 3 ‘*p*’ is to be interpreted as a site-specific process.

TIER 1 METHOD FOR WET PROCESSES – DEFAULT

The Tier 1 method is the least accurate estimation method and should be used only in cases where site-specific data on the consumption of input chemicals are not available. The Tier 1 method, unlike the Tier 2a, 2b or Tier 3 methods, is designed to give an aggregated estimate of FC emissions although its methodology appears to produce gas-specific emissions. As envisioned, Tier 1 estimates would be made simultaneously for all (or for the most important) gases listed in Tables 1Ap.1 and 1Ap.2 and can only be used if reported as a complete set.

As proposed, the Tier 1 calculation relies on a fixed set of generic emissions factors and does not account for differences among process and substrate types, individual processes or manufacturing tools. However, the members of the set would likely differ depending on the surface area of textile, carpet, leather, or paper products being manufactured. Each member of a set, which is a gas-specific emission factor, would express average emissions per unit of substrate area (textile, carpet, leather, paper) produced during manufacture.

For any class of product, the factors (members of the set) are multiplied by the annual capacity utilization (C_u, a fraction) and the annual manufacturing design capacity (C_d, in kg) of substrate processes. The product ($C_u \bullet C_d$) is an estimate of the quantity of substrate produced during the manufacture of textile, carpet, leather, or paper. The result is a set of annual emissions expressed in kg of the volatile by-products that comprise the set for each class of products. The Tier 1 formula is shown in Equation 1Ap.10.

In using Tier 1, inventory compilers should not modify, in any way, the set of the FC assumed to represent average emissions. Further, as is common practice for IPCC methods, the Tier 1 method does not allow to account for the use of emissions control technologies, and 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 1,1,2,2-Tetrafluoroethyl methyl ether to estimate the emissions of 1,1,2,2-Tetrafluoroethyl methyl ether from pad-dry-cure textiles and combine it with the results of other FC gases from a Tier 2 or Tier 3 method. The formula used to calculate Tier 1 emissions is shown in Equation 1Ap.10.

EQUATION 1AP.10
TIER 1 METHOD FOR ESTIMATION OF THE SET OF FC EMISSIONS

$$\left\{FC_k\right\}_n = \left\{EF_k \bullet C_u \bullet C_d\right\}_n \qquad (k = 1,\ldots,n)$$

Where:

$\{FC_k\}_n$ = emissions of FC volatile by-product k (kg)

Note: { }$_n$ denotes the set for each class of products (e.g. textile, carpet, leather, or paper) and n denotes the number of volatile by-products included in each set (see Tables 1Ap.1 and 1Ap.2) The estimates are only valid if made and reported for all members of the set using this Tier 1 methodology

EF_k = FC emission factor for volatile by-product k expressed as annual mass of emissions per mass of substrate for the product class (mass of volatile by-product k emitted, in kg/kg)

C_u = fraction of annual plant production capacity utilization, fraction

C_d = annual manufacturing design capacity, kg of substrate processed

TIER 2A METHOD FOR WET TREATMENT PROCESSES – PROCESS CHEMICAL-SPECIFIC PARAMETERS

The Tier 2a method uses industry-wide default values for the ratio of the mass of chemical *i* evaporated divided by the mass of chemical *i* used (EV_i), the mass fraction of volatile by-product *k* formed from the use of liquid input chemical *i* ($B_{k,i}$), the liquor concentration (C_i), the liquor pick-up (L_i), the fraction of input chemical *i* used in the wet-based manufacturing process (D_i) and the fraction of FC by-products *k* destroyed by the emissions control technology (D_k). The Tier 2a method also calculates emissions for each input chemical used on the basis of site-specific data on chemicals consumption and emissions control technologies. 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. Unlike the Tier 2b and Tier 3 methods that are explained later in this section, the Tier 2a method does not distinguish between process or substrate types, or site-specific processes. However, the Tier 2a default emission factors are formed separately for each input chemical, which, unlike the Tier 1 method, allows to account for the actual mix of input chemicals used at a particular site. Total Tier 2a emissions are equal to the sum of emissions from evaporative losses of unreacted fluorinated chemicals *i* in the production process (E_i) plus emissions of all by-products *k* (BPE_k) resulting from the conversion of all input chemicals *i* used during production, as calculated using equations 1Ap.11, and 1Ap.12 below.

EQUATION 1AP.11
TIER 2A ESTIMATION OF EMISSIONS OF UNREACTED INPUT CHEMICALS

$$E_i = C_i \bullet LP_i \bullet EV_i \bullet (1 - D_i)$$

Where:

E_i = emissions of unreacted input chemical *i* through evaporative losses, kg

C_i = liquor concentration, kg of input chemical *i* per kg of liquor

LP_i = liquor pick-up, kg of liquor containing input chemical *i* per kg of textile substrate

EV_i = ratio of the mass of chemical *i* evaporated divided by the mass of chemical *i* used

D_i = overall reduction of chemical *i*, fraction, calculated per equation 1Ap.13 (replacing '*k*' indices by '*i*' indices).

EQUATION 1AP.12
TIER 2A ESTIMATION OF BY-PRODUCT EMISSIONS

$$BRE_k = \sum_i B_{k,i} \bullet C_i \bullet LP_i \bullet (1 - D_k)$$

Where:

BPE_k = textile-based emissions of volatile by-product k generated from the conversion of all input chemicals i per mass of textile substrate, kg/kg

$B_{k,i}$ = substance emission factor, kg of volatile by-product k created per kg of input chemical i consumed

C_i = liquor concentration, kg of input chemical i per kg of liquor

LP_i = liquor pick-up, kg of liquor containing input chemical i per kg of textile substrate

D_k= overall reduction of by-product k emissions, fraction, calculated per equation 1AP.13

EQUATION 1AP.13
EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL TECHNOLOGY

$$D_k = a_k \bullet d_k \bullet UT$$

Where:

D_k = overall reduction of volatile by-product k emissions, fraction

a_k = fraction of by-product k produced from processes with emission control technologies (site-specific), fraction

d_k = Destruction Removal Efficiency (DRE) for by-product k, fraction

UT = average uptime of all abatement systems, fraction, calculated per Equation 1AP.14

EQUATION 1AP.14
UPTIME OF EMISSION CONTROL SYSTEM

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

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. UT may be set to 1 if suitable backup abatement or interlocking with the process tool is implemented for each abatement system.[7]

n = abatement system

TIER 2B METHOD FOR WET PROCESSES – PROCESS / SUBSTRATE SPECIFIC PARAMETERS

The Tier 2b method is similar to the Tier 2a approach in the sense that it is based on chemical-specific default emission factors, but the Tier 2b factors also account for the types of wet processes and/or classes of products. For the definition of 'p' compilers should refer to Box 1AP.2 Thus, the Tier 2b approach is expected to be more accurate than the Tier 2a one because the Tier 2b method reflects the type of processes used or products made in a particular manufacturing facility. Also, the Tier 2b method allows to account for the trend where some chemicals tend to be used predominantly in particular process types or products manufactured. The Tier 2b method uses industry-wide default values for the ratio of the mass of chemical *i* evaporated divided by the mass of chemical *i* used during process type or product type *p* ($EV_{i,p}$), the for the mass fraction of volatile FC by-product *k* formed from the use of input chemical *i* per mass of substrate in process type or product type *p* ($B_{k,i,p}$), the liquor concentration ($C_{i,p}$) for substrate in process type or product type *p*, the liquor pick-up ($L_{i,p}$) for substrate in process type or for product type *p*, the fraction of input chemical *i* used in the wet-based manufacturing process using process type or product type *p* and the fraction of chemical *i* evaporated or FC by-products *k* destroyed by the emissions control technology connected to tools using process type or product type *p* ($D_{i,p}$ and $D_{k,p}$).

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[7] 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.

BOX 1AP.2
APPROACHES FOR DERIVING THE TIER 2B EMISSION FACTORS AND DEFINING '*P*'

Two approaches are proposed. A first approach would be to provide separate Tier 2b emission factors depending on the actual wet treatment method used in the process. In this case, default EFs would be provided for process types such as wet finishing (e.g. pad-dry-cure and exhaust applications), low wet pickup finish applications (e.g. vacuum extraction and kiss roll), spray application, foam finishing, coating, and lamination.

Another approach would be to provide separate Tier 2b emission factors based on the type of product manufactured. In this case, default EFs would be provided for substrate types such as cellulosic and regenerated cellulosic textiles (cotton, viscose, rayon, etc.), synthetic polymers for textile (polyamides, polyesters, polypropylenes, polyurethane), lignocellulosic (flax, jute, sisal, etc.), protein-based textiles (wool, silk), leather, paper and paperboard, and technical textile polymers.

The information currently available is insufficient to determine which of the two approaches above (or a combination thereof) might be most suitable, or if separate methods should be provided to distinguish EFs by process type (a separate Tier 2b method) and by product type (an additional Tier 2c method). Further discussion is required on this point, and an analysis of how emission factors may be grouped based on different treatment process conditions (temperature, timing, type of chemicals used, etc.) should be conducted. Nevertheless, the Tier 2b methodological framework proposed here could be adapted to the (to be determined) best approach.

Although the Tier 2b method is preferred over the Tier 2a method because process-type-specific or product-type-specific emission factors are more accurate, it should be noted that the Tier 2b method presents increased complexity because the consumption of input chemicals must be allocated to each process or product type *p*. Thus, in the case where the consumption of input chemicals cannot directly be measured for each process type or product type *p*, a chemical consumption allocation model must be devised for applying the method,[8] and inventory compilers should consider the trade-off of using more accurate process-specific or product-specific emission factors versus introducing errors in the Tier 2b estimate, due to uncertainties in the allocation model.

Total Tier 2b emissions are equal to the sum of emissions from evaporative losses of unreacted fluorinated chemicals *i* used in all production processes *p* (E_i) plus emissions of all by-products *k* (BPE_k) resulting from the conversion of all input chemicals *i* used during the production of process types or substrate types *p*, as calculated using equations 1Ap.15, and 1Ap.16 below.

EQUATION 1AP.15
TIER 2B ESTIMATION OF EMISSIONS OF UNREACTED INPUT CHEMICALS

$$E_i = \sum_p \left[C_{i,p} \bullet LP_{i,p} \bullet EV_{i,p} \bullet (1 - D_{i,p}) \right]$$

Where:

E_i = emissions of unreacted input chemical i through evaporative losses, kg

$C_{i,p}$ = liquor concentration, kg of input chemical i per kg of liquor for production process p

$LP_{i,p}$ = liquor pick-up, kg of liquor containing input chemical i per kg of textile substrate for production process p

$EV_{i,p}$ = ratio of the mass of chemical i evaporated divided by the mass of chemical i used

$D_{i,p}$ = overall reduction of chemical i using production process p, fraction, calculated per equation 1AP.17 (replacing 'k' indices by 'i' indices)

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[8] For an example of how site-specific gas consumption allocation models can be developed, please see Chapter 6 Volume 3 of the *2019 Refinement*.

EQUATION 1AP.16
TIER 2B ESTIMATION OF BY-PRODUCT EMISSIONS

$$BRE_k = \sum_{i,p}\left[B_{k,i,p} \bullet C_{i,p} \bullet LP_{i,p} \bullet (1 - D_{k,p})\right]$$

Where:

BPE_k = textile-based emissions of volatile by-product k generated from the conversion of all input chemicals i per mass of textile substrate used for all production processes p, kg/kg

$B_{k,i,p}$ = substance emission factor, kg of volatile by-product k created per kg of input chemical i consumed used for production process p

$C_{i,p}$ = liquor concentration, kg of input chemical i per kg of liquor for production process p

$LP_{i,p}$ = liquor pick-up, kg of liquor containing input chemical i per kg of textile substrate for production process p

$D_{k,p}$ = overall reduction of volatile by-product k emissions from tools using production process p, fraction, calculated per Equation 1Ap.17

EQUATION 1AP.17
EMISSIONS REDUCTION IMPACT OF EMISSIONS CONTROL TECHNOLOGY

$$D_{k,p} = a_{k,p} \bullet d_{k,p} \bullet UT_p$$

Where:

$D_{k,p}$ = overall reduction of volatile by-product k emissions produced from production process p, fraction

$a_{k,p}$ = fraction of by-product k volume produced from production process p with emission control technologies (site-specific), fraction

$d_{k,p}$ = Destruction Removal Efficiency (DRE) for by-product k and production process p, fraction

UT_p = average uptime of all abatement systems connected to tools using production process p, fraction, calculated per Equation 1Ap.18

EQUATION 1AP.18
UPTIME OF EMISSION 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 production process p, fraction

$Td_{n,p}$ = The total time, in minutes, that abatement system n connected to process tool(s) running production process 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 production process p in operation. UT may be set to 1 if suitable backup abatement or interlocking with the process tool is implemented for each abatement system[9]

n = abatement system

TIER 3 METHOD FOR WET PROCESSES – SITE-SPECIFIC PARAMETERS

The Tier 3 method uses the same set of equations (equations 1Ap.15 to 1Ap.18) as the Tier 2b method. However, when using the Tier 3 method, inventory compilers need to interpret ‘p’ in these equations as a specific production process using a specific ‘recipe’. A recipe corresponds to a particular combination of input liquids under specific conditions of process duration, temperature, type of substrate, and other relevant process parameters adjusted to achieve a particular result (e.g. water or stain resistance). It is very important to note that emission factors and by-product formation rates can be strongly affected by changes in process parameters (temperature, flows and nature of input chemicals, processing time, etc.).

When using the Tier 3 method, BPE emission factors in Equation 1Ap.16 should be measured for specific processes recipes. However, a centreline process recipe may be used to establish Tier 3 emission factors for sets of ‘similar’ recipes. Recipes can be 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, process type, product, process tool, and input process gases are the same. When using the concept of ‘similarity’, inventory compilers should be able to reasonably demonstrate that emissions estimates are not biased (i.e. systematically over- or under-estimated) when using centreline process recipe(s) emission factors.

Once default Tier 2a or Tier 2b emission factors will be developed, the Tier 3 method should be used by manufacturing plants whose processes and recipes depart significantly from industry-wide patterns of use, or by manufacturing plants that may have developed specific processes whose characteristics may result in a significantly lower or higher utilization of input chemicals or formation of by-products. Further, if default Tier 2 emission factors are not available for a particular process or input chemical, manufacturing facilities should measure their site-specific emission factors and use the Tier 3 method.

It should also be noted that Tier 3 emission factors could be combined with Tier 2a or 2b default emission factors (once available) to use a hybrid method. 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. Indeed, higher accuracy might be achieved by using the Tier 3 method for specific input chemicals or site-specific processes. However, inventory compilers should not combine the Tier 1 method with any other method.

The Tier 3 method is not outlined further in this Appendix, but inventory compilers should refer to the Box 1.Ap.1 on specific technologies for the measurement of FC emissions in order to develop facility- or country-specific emission factors as a resource for implementing the Tier 3 method.

1A.3 Choice of emission factors

At the moment no representative FC emissions data can be obtained for textile, carpet, leather and paper industries to derive the Tier 1 or Tier 2 default emission factors. Thus, the Tier 3 methods is the only practical means to estimate emissions from this sector, where individual manufacturing sites will have to use measured emission factors (equipment-specific, process-specific, or site-specific). In this case, applying the Tier 3 methods and reporting emission factors across representative manufacturing sites will become essential in building a database of emission factors that can later be used to derive the Tier 1 and Tier 2 emission factors. Countries are encouraged to develop country-specific emission factors based on surveys of representative subsets of sources. Countries are also encouraged to work with equipment manufacturers and users of such equipment to measure

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[9] 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.

equipment-specific, process-specific, or site-specific emission factors, with the aim of developing representative default emission factors that could eventually be used for site-specific, domestic, or industry-wide inventories. It is *good practice* to clearly and transparently document such emission factors. To support development of representative default emission factors, inventory compilers are encouraged to submit measurements of emission factors to the IPCC Emission Factor Database (EFDB).

1A.4 Choice of activity data

Activity data for the textile, carpet, leather and paper industries consist of data on gas or finishing agent sales/purchases and/or production figures (surface area or kg of substrate used during the textile treatments). For plasma and wet-based treatments the more data-intensive Tier 2 and Tier 3 methods, gas consumption and finishing agent data at the company or plant-level are necessary. The preferred methodologies for data collection are described in Box 1Ap.1. For Tiers 2 and 3, countries should create a national textile industry database with relevant data or information on textile companies, types of production/treatment, annual production data, consumption of chemicals and other relevant parameters. For the Tier 1 methods, inventory compilers will need to determine the total surface area of textile substrates treated during the reporting year for plasma or the mass of textile substrates treated for wet-based processes in the reporting year. The best sources of either gas/finishing agent usage data or substrate area per kg data are the owners and operators of the textile manufacturing facilities in each country.

1A.5 Reporting and Documentation

It is *good practice* to document and archive all information required to produce equipment-specific, process-specific or site-specific emission factors and national emission inventory estimates as outlined in Volume 1, Section 6.11. The inventory should include summaries of methods used and references to source data such that the reported emission estimates are transparent and steps in their calculation may be retraced. It is suggested that any inventory value outside the 95 percent confidence range of the data population variance be confirmed with the data source. Use of standard measurement methods improves the consistency of the resulting data and knowledge of the statistical properties of the data. Large differences should be explained and documented. In addition, the methods applied and references should be documented. It is *good practice* to conduct quality control checks and quality assurance procedures as outlined in Volume 1, Chapter 6. Inventory compilers are encouraged to use higher tier Quality assurance and quality control (QA/QC) for *key categories* as identified in Volume 1, Chapter 4. Transparent reporting of emissions factors will be required to ensure that representative default emission factors can be derived. Efforts to increase transparency should also take into account the protection of confidential business information related to specific gases or finishing agents used.

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