

# CHAPTER 4

---

## METAL INDUSTRY EMISSIONS

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

## **Authors**

### **Section 4.1**

Jerry Marks (USA)

### **Section 4.2**

Jonathan Lubetsky (USA) and Bruce A. Steiner (USA)

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

### **Section 4.3**

Tor Faerden (Norway), Jonathan S. Lubetsky (USA), Tor Lindstad (Norway), Sverre E. Olsen (Norway), and Gabriella Tranell (Norway)

### **Section 4.4**

Jerry Marks (USA), William Kojo Agyemang-Bonsu (Ghana), Mauricio Firmento Born (Brazil), Laurel Green (Australia), Halvor Kvande (Norway), Kenneth Martchek (USA), and Sally Rand (USA)

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

### **Section 4.5**

Gabriella Tranell (Norway) and Tom Tripp (USA)

### **Section 4.6**

Jonathan S. Lubetsky (USA) and Jerry Marks (USA)

### **Section 4.7**

Jonathan S. Lubetsky (USA)

### **Section 4.8**

David Sydney Wong (New Zealand)

## **Contributing Authors**

### **Section 4.2**

Robert Lanza (USA)

Jan Hendrik Reimink (WSA/Netherlands)

### **Section 4.4**

Vince Van Son (USA), Pablo Alonso (France), Ron Knapp (Australia), Stéphane Gauthier (Canada), Michel Lalonde (Canada), Hézio Ávila de Oliveira (Brazil), and Chris Bayliss (UK)

Simon Gaboury (Canada), Jerry Y. Marks (USA) and Andrey V. Panov (Russian Federation)

### **Sections 4.4 and 4.8**

Xin Bo (China), Xiping Chen (China)

### **Section 4.8**

Michalopoulou Eleni (UK), Hanno Vogel (Germany) and Youming Yang (China)

## Contents

45			
46	4	Metal Industry Emissions.....	4.7
47	4.1	Introduction .....	4.7
48	4.2	Iron & Steel and Metallurgical Coke Production .....	4.8
49	4.2.1	Introduction .....	4.10
50	4.2.2	Methodological issues .....	4.10
51	4.2.2.1	Choice of method: Metallurgical coke production .....	4.11
52	4.2.2.2	Choice of method: iron and steel production.....	4.17
53	4.2.2.3	Choice of emission factors .....	4.22
54	4.2.2.4	Choice of activity data .....	4.28
55	4.2.2.5	Completeness.....	4.29
56	4.2.2.6	Developing a consistent time series.....	4.32
57	4.2.3	Uncertainty assessment .....	4.32
58	4.2.4	Quality Assurance/Quality Control (QA/QC), Reporting and Documentation .....	4.33
59	4.3	Ferroalloy Production .....	4.34
60	4.4	Primary Aluminium Production .....	4.35
61	4.4.1	Introduction to Primary Aluminium .....	4.35
62	4.4.2	Methodological issues for primary aluminium production .....	4.36
63	4.4.2.1	Choice of Method for CO <sub>2</sub> emissions from primary aluminium production .....	4.36
64	4.4.2.2	Choice of emission factors for CO <sub>2</sub> emissions from primary aluminium production.....	4.36
65	4.4.2.3	Choice of method for PFCs .....	4.37
66	4.4.2.4	Choice of emission factors for PFCs .....	4.44
67	4.4.2.5	Choice of activity data.....	4.47
68	4.4.2.6	Completeness.....	4.47
69	4.4.2.7	Developing a consistent time series.....	4.47
70	4.4.3	Uncertainty assessment for primary aluminium production.....	4.48
71	4.4.3.1	Emission factor uncertainties.....	4.48
72	4.4.3.2	Activity data uncertainties .....	4.49
73	4.4.4	Quality Assurance/Quality Control (QA/QC) Reporting and Documentation for primary aluminium	
74		production .....	4.49
75	4.4.4.1	Quality Assurance/Quality Control (QA/QC) .....	4.49
76	4.4.4.2	Reporting and documentation.....	4.50
77	4.4.5	Methodological issues for alumina production .....	4.52
78	4.4.5.1	Alternative alumina refining processes .....	4.52
79	4.4.5.2	Choice of method .....	4.56
80	4.4.5.3	Choice of emission factors for alumina production.....	4.61
81	4.4.5.4	Choice of activity data.....	4.62
82	4.4.5.5	Completeness.....	4.63
83	4.4.5.6	Developing a consistent time series.....	4.63
84	4.4.6	Uncertainty assessment for alumina production.....	4.63

85	4.4.6.1	Emission factor uncertainties.....	4.63
86	4.4.6.2	Activity data uncertainties .....	4.63
87	4.4.7	Quality Assurance/Quality Control (QA/QC), Reporting and Documentation for alumina	
88		production .....	4.66
89	4.4.7.1	Quality Assurance / Quality Control (QA/QC) .....	4.66
90	4.4.7.2	Reporting and Documentation .....	4.67
91	4.5	Magnesium Production .....	4.68
92	4.6	Lead Production.....	4.69
93	4.7	Zinc Production .....	4.70
94	4.8	Rare Earths Production .....	4.71
95	4.8.1	Introduction .....	4.71
96	4.8.2	Methodological Issues .....	4.72
97	4.8.2.1	Choice of method for CO <sub>2</sub> emissions from primary rare earth metal production .....	4.72
98	4.8.2.2	Choice of emission factors for CO <sub>2</sub> emissions from primary rare earth metal production ..	4.75
99	4.8.2.3	Choice of method for PFCs .....	4.76
100	4.8.2.4	Choice of emission factors for PFCs .....	4.80
101	4.8.2.5	Choice of activity data & emission factors .....	4.81
102	4.8.2.6	Completeness.....	4.81
103	4.8.2.7	Developing a consistent time series.....	4.81
104	4.8.3	Uncertainty assessment .....	4.82
105	4.8.3.1	Emission factor uncertainties.....	4.82
106	4.8.3.2	Activity data uncertainties .....	4.83
107	4.8.4	Quality Assurance/Quality Control (QA/QC), Reporting and Documentation .....	4.83
108	4.8.4.1	Quality Assurance/Quality Control (QA/QC) .....	4.83
109	4.8.4.2	Reporting and Documentation .....	4.84
110	Reference	.....	4.85

## Equations

112	Equation 4.1 (updated)	Emissions from Coke production (tier 1a).....	4.14
113	Equation 4.1a (new)	CO <sub>2</sub> Emissions from metallurgical Coke production (tier 1b) .....	4.14
114	Equation 4.2 (unchanged)	CO <sub>2</sub> Emissions from onsite coke production (tier 2) .....	4.15
115	Equation 4.4 (unchanged)	CO <sub>2</sub> emissions from iron and steel production (Tier 1) .....	4.18
116	Equation 4.5(unchanged)	CO <sub>2</sub> emissions from production of pig iron not processed into steel (Tier 1) ...	4.19
117	Equation 4.6 (unchanged)	CO <sub>2</sub> emissions from production of direct reduced iron (Tier 1).....	4.19
118	Equation 4.7 (unchanged)	CO <sub>2</sub> emissions from sinter production (Tier 1) .....	4.19
119	Equation 4.8 (unchanged)	CO <sub>2</sub> emissions from pellet production (Tier 1) .....	4.19
120	Equation 4.9 (unchanged)	CO <sub>2</sub> emissions from iron & steel production (Tier 2) .....	4.20
121	Equation 4.10 (unchanged)	CO <sub>2</sub> emissions from sinter production (Tier 2) .....	4.20
122	Equation 4.11(unchanged)	CO <sub>2</sub> emissions from direct reduced iron production (Tier 2) .....	4.21

## Second-order Draft

123	Equation 4.12 (unchanged)	CH <sub>4</sub> emissions from sinter production (Tier 1) .....	4.22
124	Equation 4.13 (unchanged)	CH <sub>4</sub> emissions from blast furnace production of pig iron (Tier 1) .....	4.22
125	Equation 4.14 (unchanged)	CH <sub>4</sub> emissions from direct reduced iron production (Tier 1) .....	4.22
126	Equation 4.25 (updated)	HVAE PFC emissions (Tier 1 method) .....	4.38
127	Equation 4.25a (new)	LVAE PFC emissions (Tier 1 method) .....	4.39
128	Equation 4.26 (updated)	HVAE PFC emissions by Slope method (Tier 2A and Tier 3A methods) .....	4.39
129	Equation 4.27 (unchanged)	HVAE PFC emissions by Overvoltage method (Tier 3 method) .....	4.40
130	Equation 4.27a (new)	HVAE PFC emissions (Tier 2b and Tier 3b method ) .....	4.41
131	Equation 4.27b (new)	HVAE PFC emissions (Tier 2b and Tier 3b method ) .....	4.41
132	Equation 4.27c (new)	LVAE PFC emissions (Tier 2 and Tier 3 methods) .....	4.42
133	Equation 4.27d (new)	Emission rate coefficients for HVAE PFC (Tier 2b method) .....	4.46
134	Equation 4.27e (new)	Tier 1: Sintering process emissions based on alumina production data .....	4.56
135	Equation 4.27f (new)	Tier 3: Emissions based on carbonate raw material inputs to the sintering kiln .....	4.58
136	Equation 4.27g (new)	Emissions captured during carbonization process and contained in produced	
137		sodium carbonate .....	4.59
138	Equation 4.27h (new)	Emissions from un-calcined SKD not recycled to the kiln .....	4.59
139	Equation 4.27i (new)	Weighted average content CO <sub>2</sub> in 'i' Bauxites (Nephelines) .....	4.60
140	Equation 4.27j (new)	Emissions from Bauxites (Nephelines) residue .....	4.60
141	Equation 4.27k (new)	Emissions from carbon-bearing non-fuel materials .....	4.60
142	Equation 4.27l (new)	CO <sub>2</sub> absorption through use of circulating water collected from bauxite/nepheline	
143		storage residue area and/or absorption through bauxite residue neutralization .	4.60
144	Equation 4.35 (new)	Process CO <sub>2</sub> Emissions from anode consumption (Tier 1) .....	4.74
145	Equation 4.36 (new)	Process CO <sub>2</sub> Emissions from anode consumption (Tier 3) .....	4.74
146	Equation 4.37 (new)	PFC Emissions (Tier 1 and Tier 3) .....	4.79

## Figures

148	Figure 4.1 (unchanged)	Illustration of main processes for integrated iron and steel production* .....	4.9
149	Figure 4.6 (updated)	Estimation of CO <sub>2</sub> emissions from metallurgical coke production .....	4.16
150	Figure 4.7 (unchanged)	Decision tree for estimation of CO <sub>2</sub> emissions from iron and steel production ...	4.17
151	Figure 4.8 (unchanged)	Decision tree for estimation of CH <sub>4</sub> emissions from iron and steel production ...	4.18
152	Figure 4.8a (new)	Energy or IPPU CO <sub>2</sub> emissions allocation in an integrated iron and steel facility	4.30
153	Figure 4.12 (updated)	Decision tree for calculation of PFC emissions from primary aluminium	
154		production .....	4.43
155	Figure 4.12a (new)	Alumina production processes .....	4.53
156	Figure 4.12b (new)	Decision tree for estimation of CO <sub>2</sub> emissions from alumina production .....	4.57
157	Figure 4.17 (new)	Decision tree for calculation of CO <sub>2</sub> emissions from primary rare earth (RE) metal	
158		production .....	4.73
159	Figure 4.18 (new)	Decision tree for calculation of PFC emissions from primary rare earth (RE) metal	
160		production .....	4.78
161			

## Tables

163	Table 4.1a (new)	Emission allocation from metallurgical coke production.....	4.11
164	Table 4.1b (new)	Tiers to Estimate CO <sub>2</sub> emissions from metallurgical coke production .....	4.13
165	Table 4.1 (updated)	Tier 1 default CO <sub>2</sub> emission factors for coke production and Iron&steel production	4.23
166	Table 4.2 (updated)	Tier 1 default CH <sub>4</sub> emission factors for coke production and Iron&Steel production	4.27
167	Table 4.3 (updated)	Tier 2 material-specific carbon contents for Iron&Steel production (kg C/kg) .....	4.28
168	Table 4.4 (updated)	Uncertainty ranges .....	4.32
169	Table 4.15 (updated)	Technology specific default emission factors for the calculation of HVAE and LVAE	
170		emissions from aluminium production (Tier 1 method).....	4.44
171	Table 4.16 (updated)	Technology specific coefficients for the calculation of HVAE PFC emissions from	
172		Aluminium production using slope methodology (Tier 2a method) .....	4.45
173	Table 4.16a (new)	Specific HAVE-PFC emission rate coefficients based on the anode effect duration as	
174		calculated by (Tier 2b method).....	4.45
175	Table 4.16b (new)	Technology specific default emission factors for the calculation of LVAE PFC emissions	
176		from aluminium production (Tier 2 Method) .....	4.46
177	Table 4.17 (updated)	Good practice reporting information for calculating CO <sub>2</sub> and PFC emissions from	
178		aluminium production by tier .....	4.51
179	Table 4.17a (new)	Technology specific default emission factors for the calculation of CO <sub>2</sub> emissions from	
180		alternative sintering processes (Tier 1 method).....	4.61
181	Table 4.17b (new)	Default uncertainty values for Bauxite/nepheline sintering process .....	4.65
182	Table 4.26 (new)	Tier 1 default emission factors for calculating CO <sub>2</sub> emissions from anode	
183		consumption .....	4.75
184	Table 4.27 (new)	Data sources and uncertainties for parameters used in Tier 3 method for CO <sub>2</sub> emissions	
185		from anode consumption .....	4.76
186	Table 4.28 (new)	Tier 1 default emission factors and uncertainty ranges for the calculation of PFC	
187		emissions from rare earth production .....	4.80
188	Table 4.29 (new)	Data sources and uncertainties for parameters used in Tier 3 method for PFC	
189		emissions .....	4.81
190	Table 4.30 (new)	Good practice reporting information for calculating CO <sub>2</sub> and PFC emissions from rare	
191		earth metal production by Tier .....	4.84

## Boxes

193	Box 4.1a (new)	Fully automated anode effect intervention strategies for PFC emissions .....	4.36
194	Box 4.2 (updated)	High and low voltage anode effect description .....	4.37
195	Box 4.2a (new)	High voltage anode effects following start-up of electrolysis cells .....	4.42
196	Box 4.3 (new)	Anode effect description (for rare earth metal production by fluoride electrolysis)...	4.76

Second-order Draft

198 **4 METAL INDUSTRY EMISSIONS**

199 **4.1 INTRODUCTION**

200 No Refinement

201

202

## 4.2 IRON & STEEL AND METALLURGICAL COKE PRODUCTION

The production of iron and steel leads to emissions of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). This chapter provides guidance for estimating emissions of CO<sub>2</sub> and CH<sub>4</sub>.<sup>1</sup>

- 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<sub>2</sub> and CH<sub>4</sub> 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 basic oxygen steelmaking furnaces (BOFs), or in some cases open hearth furnaces (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.

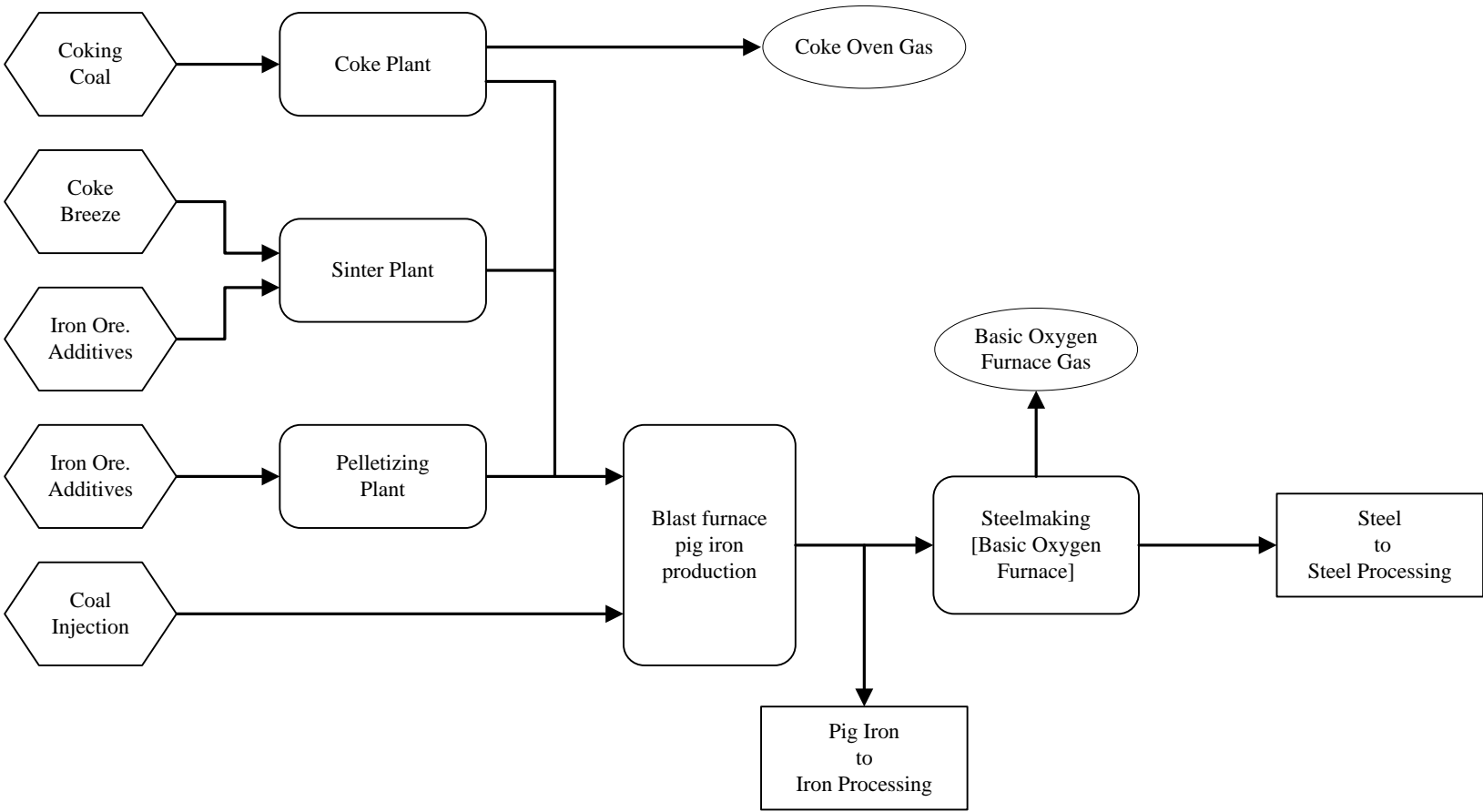
### Metallurgical coke production:

Metallurgical coke production is considered to be an energy use of fossil fuel, and as a result emissions should be reported in Category 1A of the Energy Sector. The methodologies 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. All fuel consumed in this source category not allocated as inputs to the sinter plants, pelletisation plants and blast furnace should be regarded as fuel combustion, which is dealt with and reported in the Energy Sector (see Volume 2: Energy).

<sup>1</sup> No methodologies are provided for N<sub>2</sub>O 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 (unchanged) 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

[This section, 4.2.2, is an update/elaboration 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 coke making process comprises: (1) coal handling and preparation, including the transportation, discharges, storage, crushing, bed blending, that in all the cases causes dust emissions, but not GHGs, and (2) coke oven battery operations, including coal charging, heating and firing of the chambers, coking, coke pushing and quenching and coke handling (i.e. storing, transporting, crushing and screening), where GHGs occurring. The coking refers to the carbonization process that takes place in the ovens, and consists in a thermal distillation that removes practically all the volatile matter from coal to produce coke in the form of gases or liquids. Related with the treatment of these by-products, there are two technological options:

- coke making process with a by-products recovery plants, where the organic liquids (like tar and light oil) are recovered.
- non-recovery coke making process where all the by-products are burned. This process is usually accompanied by heat recovery and in many cases also the cogeneration of electricity.

During metallurgical coke production two types of emissions occur:

- Direct emissions discharged into the atmosphere through stacks, comprising the emissions originated in the carbonisation (a fuel transformation process) and those from fuel combustion. These emissions should be reported under in the Energy Sector, in Manufacture of Solid Fuels in IPCC category 1.A.1.c i. The methodology is presented here due to the significant overlap of the activity data used for iron and steel production GHG methodological calculations.
- Fugitive emissions comprise of:
  - diffuse emissions related to the sources not associated with stacks, that occur during regular or irregular operation, related to the transportation of coke, ascension pipes, coke pushing, quenching and leakages at the battery and that in general terms are difficult to quantify. CH<sub>4</sub> is the only GHG with significant diffuse emissions. These emissions should be reported under the Energy Sector, in Fugitive emissions subsection (IPCC category 1.B.1c) and the methodology to estimate them are presented in Chapter 4 Volume 2 of the *2019 Refinement*.
  - flaring, which is used under emergencies and COG consumer maintenance, and where CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions occurs. In integrated facilities is usual to burn COG jointly with blast furnace gas and other gases produced, such as converter gas. These emissions should be reported under the Energy Sector: (1) CH<sub>4</sub> and N<sub>2</sub>O, in Fugitive emissions subsection (IPCC category 1.B.1c) and the methodology to estimate them are presented in Chapter 4 Volume 2 of the *2019 Refinement*, and (2) CO<sub>2</sub> should be also reported under IPCC 1.B.1c category, except the situation when the simplified mass-balance approach is chosen (Tier 1.b), and emissions should be reported with direct emissions under the category 1.A.1.c i.

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

Second-order Draft

TABLE 4.1A (NEW) EMISSION ALLOCATION FROM METALLURGICAL COKE PRODUCTION					
Process and gases		Carbonisation process emissions	Combustion emissions	Fugitive	
				Diffuse emissions	Flaring
Coal charging	CO <sub>2</sub>			NO	
	CH <sub>4</sub>			1.B.1c	
	N <sub>2</sub> O			NO	
Heating and firing of the chambers	CO <sub>2</sub>		1.A.1.c	NS	
	CH <sub>4</sub>			1.B.1c	
	N <sub>2</sub> O			NO	
Coking	CO <sub>2</sub>	1.A.1.c		NS	
	CH <sub>4</sub>			1.B.1c	
	N <sub>2</sub> O			NO	
Coke pushing	CO <sub>2</sub>			NS	
	CH <sub>4</sub>			1.B.1c	
	N <sub>2</sub> O			NO	
Coke quenching	CO <sub>2</sub>			NS	
	CH <sub>4</sub>			1.B.1c	
	N <sub>2</sub> O			NO	
Emergencies and COG consumers maintenance	CO <sub>2</sub>			NS	1.B.1c or 1.A.1.c (as described above)
	CH <sub>4</sub>			1.B.1c	1.B.1c
	N <sub>2</sub> O				
Note: NS: Not significant, NO: not occurring					

### 4.2.2.1 CHOICE OF METHOD: METALLURGICAL COKE PRODUCTION

This section outlines three tiers for calculating CO<sub>2</sub> emissions and two tiers for calculating CH<sub>4</sub> emissions from metallurgical coke production<sup>1</sup>.

The tier used to estimate emissions will depend on the quantity and quality of data that are available for national inventory compilers. If the category is key, it is good practice to estimate emissions using a Tier 2 or Tier 3 approach. The decision tree in Figure 4.6 will help in selecting which tier should be used to estimate CO<sub>2</sub> emissions. For CH<sub>4</sub> emissions, the decision tree is presented in Figure 4.8.

The Tier 1 method to estimate CO<sub>2</sub> emissions comprises two approaches, depending on the type of activity data available:

- Tier 1 a: In case only metallurgical coke production data is available, the methodology is based on the use of a default emission factor given in Table 4.1, allocating to the different type of technology. This methodology takes into consideration default emission factors derived from stack measurements, comprising the emissions from carbonization (fuel transformation) and combustion, having said that there are no practicable measurements distinguish between both. If the country chooses this approach the

<sup>1</sup> No methodologies are provided for N<sub>2</sub>O. These emissions are likely to be negligible, but countries can develop country-specific methods based on research data.

corresponding CO<sub>2</sub> fugitive emissions should be estimated according to the methodology described in Section 4.3.3 Chapter 4 Volume 2 of the *2019 Refinement* (category 1.B.1c).

- Tier 1 b: If, in addition to data on metallurgical coke production the country has data on the consumption of metallurgical coal, then it is *good practice* to use a simplified carbon mass balance approach, assuming that all coke oven gas is combusted for coke production. Under this assumption, fugitive emissions are included as well as the emissions from consumption of the by-products. In many countries, the statistics related to these data are available and regularly updated, so the collection of these activity data should not represent a serious obstacle. For Tier 1 this one is the preferred method.

The Tier 2 method to estimate CO<sub>2</sub> emissions is based on the carbon mass balance approach, using national statistical data of the carbonaceous materials inputs and outputs from the coke production process. If country-specific carbon content data derived from national fuel characteristics are available, it is *good practice* to use them. Otherwise an hybrid methodology<sup>1</sup> can be used, selecting the default carbon content data provided in Table 4.3.

The Tier 3 method to estimate CO<sub>2</sub> emissions requires plant-specific emissions measurement data, combined with plant-specific activity data and plant-specific carbon content data for carbon mass balance approach, for those sources where measurement data is not available.

Table 4.1b summarizes the activity data and the emission factors to be used to estimate CO<sub>2</sub> emissions for the different tiers.

---

<sup>1</sup> Hybrid methodology, refers that is based on a complete carbon balance approach, with default carbon content.

Second-order Draft

<b>TABLE 4.1B (NEW)</b> <b>TIERS TO ESTIMATE CO<sub>2</sub> EMISSIONS FROM METALLURGICAL COKE PRODUCTION</b>					
<b>Method</b>	<b>AD</b>	<b>EF</b>	<b>Technology</b>	<b>Limitations/Comments</b>	<b>Tier</b>
Production-based	Metallurgical coke produced in the country	Default EF (Table 4.1)	This method can be applied using recovery and non-recovery by-products technologies.	The production-based method should not be used for estimating emissions in conjunction with a carbon balance approach for iron and steel production, where the coke ovens operate within an integrated steelworks, due to the risk of double-counting emissions.	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 the non-by-product-recovery process.	If this method is applied, then no estimates of CO <sub>2</sub> from fugitives and flaring from coke production using the methods described in the Energy volume should be occurred as this would be a double-counting.	Tier 1b
National Carbon Balance method (country-specific EFs) –	National data on all INPUTS (raw materials and fuels: coking coal), and on all OUTPUTS (products and by-products: coke, COG, tars and benzenes, flaring)	Country-specific carbon content of inputs and outputs	(All technologies)	If country-specific carbon contents are not available for all inputs and outputs, the default carbon content from Table 4.3 may be applied with a hybrid method, but this will be considered as a Tier 1 / Tier 2 approach which is not appropriate for <i>key category</i> .	Tier 2
Aggregated of installation-specific carbon balance method (country-specific EFs)	Installation-level data on all INPUTS ( <i>as described above</i> ) and OUTPUTS ( <i>as described above</i> )	Installation-specific carbon content of inputs and outputs	(All technologies)		Tier 3a
Installation-level measurement data	n/a	n/a	(All technologies)	Emissions measurement data must be complete for all emission sources at the coke plant, and must comply with measurement protocols and QA requirements consistent with ISO 14404.	Tier 3b

330

331 The methodologies to estimate CH<sub>4</sub> emissions are related with the emissions from quenching towers and stacks,  
 332 using default emission factors (Tier 1a) or measurements (Tier 3). There is no Tier 2 method. The methodology

to estimate CH<sub>4</sub> fugitive emissions is described in Section 4.3.3 Chapter 4 Volume 2 of the *2019 Refinement* (category 1.B.1c).

## TIER 1 METHOD

### Tier 1 a: Production based method

To apply for this method, the amount of tonnes of coke produced in the country and the use of a default emission factor, given in Table 4.1, are required. The following equation is used:

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

$$E_{CO_2, energy} = CO \bullet EF_{CO_2} \text{ and } E_{CH_4, energy} = CO \bullet EF_{CH_4}$$

Where:

$E_{CO_2, energy}$  or  $E_{CH_4, energy}$  = emissions of CO<sub>2</sub> or CH<sub>4</sub> from coke production, in kg CO<sub>2</sub> or kg CH<sub>4</sub>, to be reported under the Energy Sector, category 1.A.1c.

CO = quantity of coke produced nationally, tonnes

EF= emission factor, tonnes CO<sub>2</sub>/tonne coke production or tonnes CH<sub>4</sub>/tonne coke production (Table 4.1)

### Tier 1 b: Simplified carbon balance method

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 metallurgical 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 4.1A (NEW)**  
**CO<sub>2</sub> EMISSIONS FROM METALLURGICAL COKE PRODUCTION (TIER 1B)**

$$E_{CO_2, energy} = [CC \bullet C_{CC} - CO \bullet C_{CO}] \bullet \frac{44}{12}$$

Where:

$E_{CO_2, energy}$  = CO<sub>2</sub> 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

CO = quantity of coke produced in the country, tonnes

$C_{CC}$  = default carbon content of metallurgical coal (tonnes C / tonnes coal)

$C_{CO}$  = default carbon content of metallurgical coke (tonnes C / tonnes coal)

## TIER 2 METHOD

The Tier 2 method to estimate CO<sub>2</sub> emissions is appropriate in case national statistics on process inputs and outputs from integrated and non-integrated coke production processes are available. The following equation with a country specific carbon content given in Table 4.3 is used:

**EQUATION 4.2 (UNCHANGED)**  
**CO<sub>2</sub> EMISSIONS FROM ONSITE COKE PRODUCTION (TIER 2)**

$$E_{CO_2, \text{energy}} = \left[ CC \cdot C_{CC} + \sum_a (PM_a \cdot C_a) + BG \cdot C_{BG} - CO \cdot C_{CO} - COG \cdot C_{COG} - \sum_b (COB_b \cdot C_b) \right] \cdot \frac{44}{12}$$

Where:

$E_{CO_2, \text{energy}}$  = CO<sub>2</sub> emissions to be reported in the Energy Sector category 1.A.1c (kg)

CC = quantity of coke produced in the country (kg)

PM<sub>a</sub> = quantity of other process material *a*, other than those listed as separate terms, such as natural gas, fuel oil or converter gas, consumed in the country for metallurgical coke production (kg)

BG = quantity of blast furnace gas consumed in coke ovens in the country (kg)

CO = quantity of metallurgical coke produced in the country (kg)

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

COB<sub>b</sub> = quantity of coke oven by-product *b* produced, and transferred either offsite or to other facilities (kg), including flaring

C<sub>x</sub> = country specific carbon content of material input or output *x*, (kg C / kg material)

Note: CO<sub>2</sub> emissions from flaring are deducted in the carbon mass balance because the corresponding emissions are estimated with the methodology described in Chapter 4 Volume 2 of the *2019 Refinement*.

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*.

### 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.

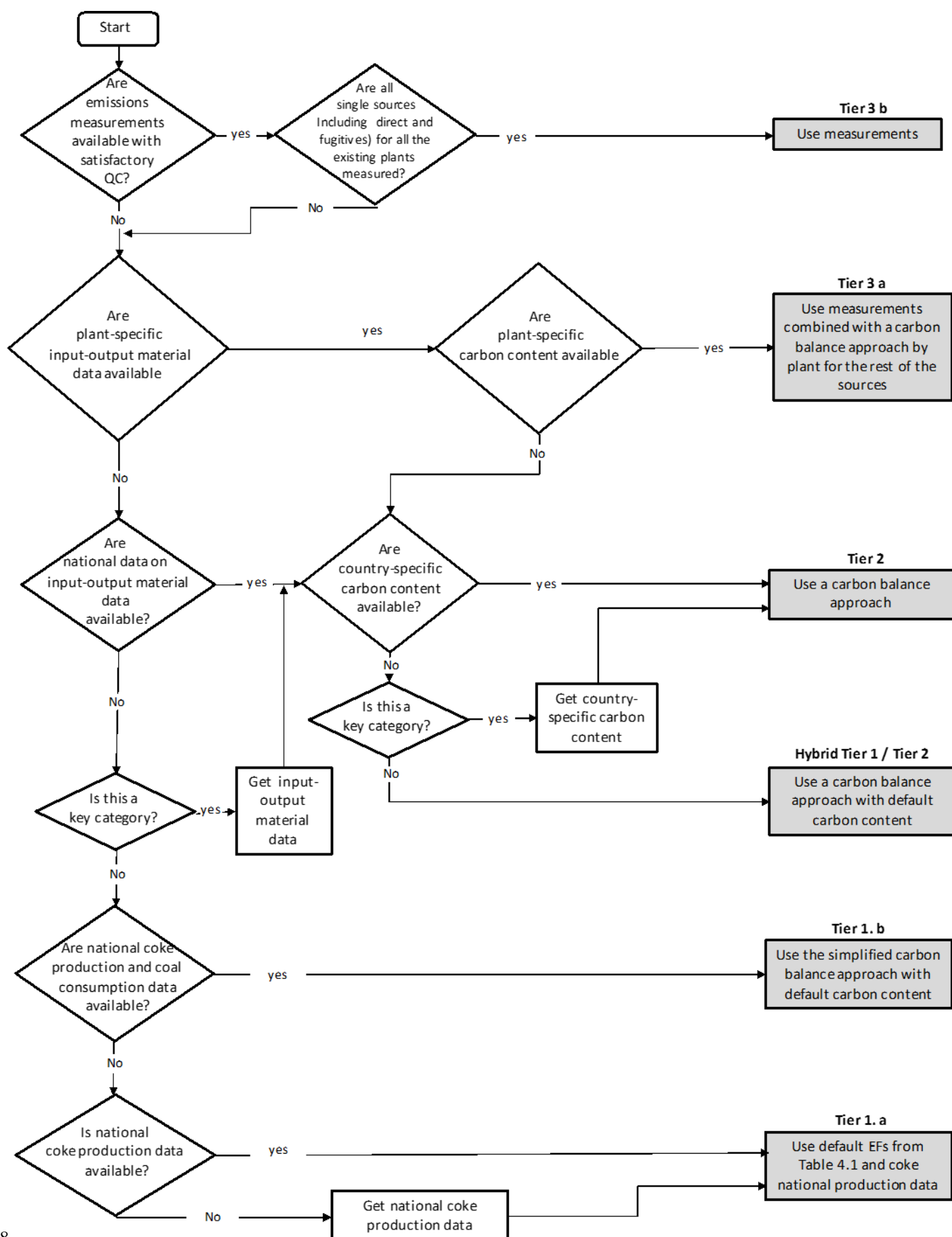
Tier 3 comprises two approaches for CO<sub>2</sub> and only one for CH<sub>4</sub>:

- For CO<sub>2</sub> and CH<sub>4</sub>: monitoring data of direct sources;
- For CO<sub>2</sub>: carbon mass balance approach, with plant-specific carbon content of all the materials used and produced.

If actual measured CO<sub>2</sub>/CH<sub>4</sub> emissions data are available from all direct single sources present in all the coke production plants in the country, these data could be aggregated and used directly to account the national emissions from metallurgical coke production. Total national emissions will be equal to the sum of emissions reported from each facility. It is a *good practice* to apply a QA/QC for the monitoring data, following the recommendations included in Volume 1 Chapter 6 of the *2019 Refinement*.

In case the facility-specific CO<sub>2</sub> emissions data are not available for part or for all sources in the country, the CO<sub>2</sub> emissions for the unmeasured sources could be estimated from plant-specific activity data applying a carbon mass balance with country specific carbon content, using Equation 4.2.

407 **Figure 4.6 (updated) Estimation of CO<sub>2</sub> emissions from metallurgical coke production**



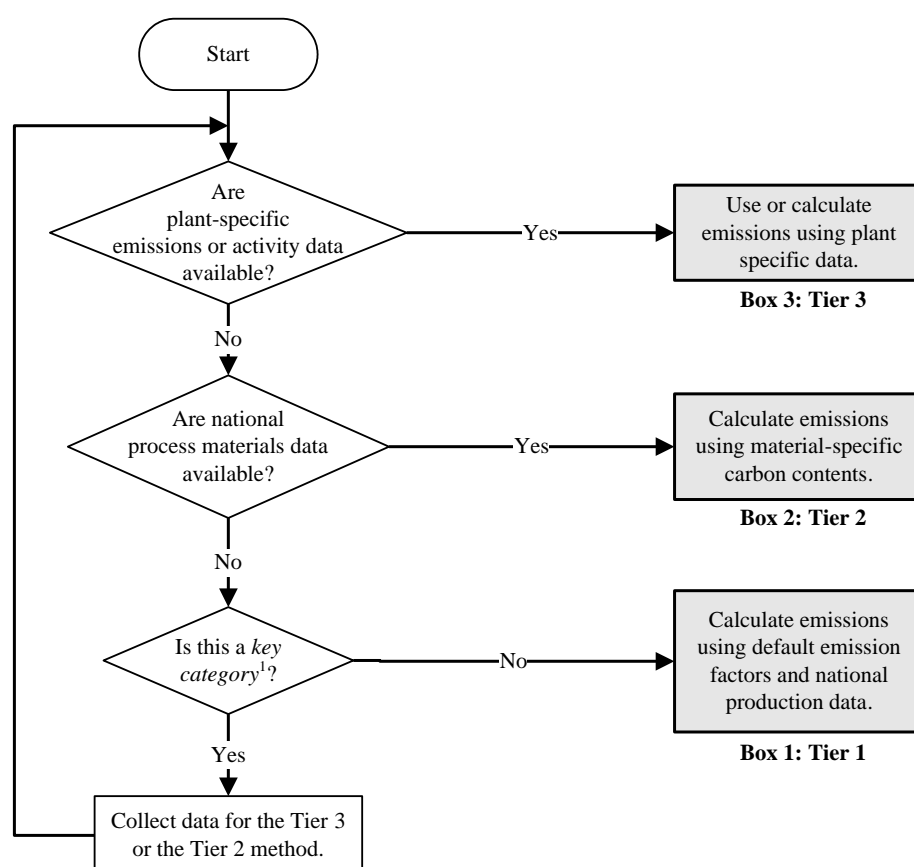


### 4.2.2.2 CHOICE OF METHOD: IRON AND STEEL PRODUCTION

These section outline three tiers for calculating CO<sub>2</sub> emissions and two tiers for calculating CH<sub>4</sub> emissions from iron and steel production, Decision Tree for Estimation of CO<sub>2</sub> Emissions from Iron & Steel Production and Decision Tree for Estimating of CH<sub>4</sub> Emissions from Iron and Steel Production.

The Tier 1 method is based on national production data and default emission factors. It may lead to errors due to its reliance on assumptions rather than actual data for the quantity of inputs into the sinter production and iron and steel production sector that contribute to CO<sub>2</sub> emissions. Therefore, the Tier 1 is appropriate only if iron and steel production is not a *key category*.

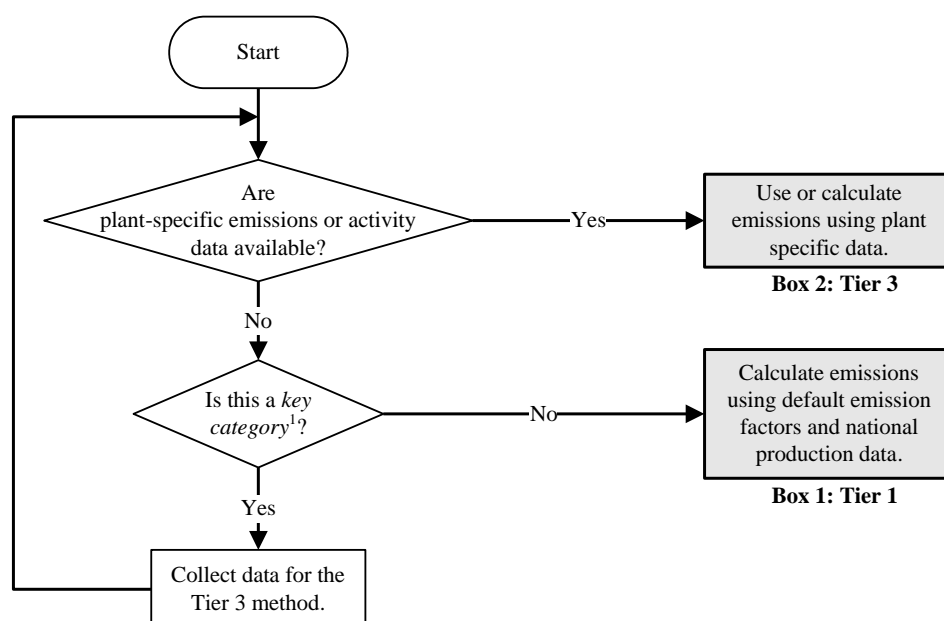
**Figure 4.7(unchanged) Decision tree for estimation of CO<sub>2</sub> emissions from iron and steel production**



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.

**Figure 4.8 (unchanged) Decision tree for estimation of CH<sub>4</sub> emissions from iron and steel 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.

## METHODOLOGY FOR ESTIMATING CO<sub>2</sub> 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 Basic Oxygen Furnaces (BOF), Electric Arc Furnaces (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 pig iron production in blast furnace 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 steps.

Equation 4.6 calculates CO<sub>2</sub> emissions from production of Direct Reduced Iron (DRI) for the Tier 1 method using a CO<sub>2</sub> emission factor.

It is also *good practice* to estimate separately the emissions from sinter production and national pellet production, using Equations 4.7 and 4.8. Equations 4.7 and 4.8 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.

Total emissions are the sum of Equations 4.4 to 4.8.

**EQUATION 4.4 (UNCHANGED)**  
**CO<sub>2</sub> EMISSIONS FROM IRON AND STEEL PRODUCTION (TIER 1)**

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

## Second-order Draft

**EQUATION 4.5(UNCHANGED)****CO<sub>2</sub> EMISSIONS FROM PRODUCTION OF PIG IRON NOT PROCESSED INTO STEEL (TIER 1)**

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

**EQUATION 4.6 (UNCHANGED)****CO<sub>2</sub> EMISSIONS FROM PRODUCTION OF DIRECT REDUCED IRON (TIER 1)**

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

**EQUATION 4.7 (UNCHANGED)****CO<sub>2</sub> EMISSIONS FROM SINTER PRODUCTION (TIER 1)**

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

**EQUATION 4.8 (UNCHANGED)****CO<sub>2</sub> EMISSIONS FROM PELLET PRODUCTION (TIER 1)**

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

**Where:**

$E_{CO_2, \text{non-energy}}$  = emissions of CO<sub>2</sub> 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<sub>2</sub>/tonne  $x$  produced

**Tier 2 method**

The Tier 2 method is appropriate in case the inventory compiler has an 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 a number of other process inputs and outputs that could be considered under Tier 2. 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. The Tier 2 method will produce a more accurate estimation comparing to the Tier 1 method because it takes into account the actual quantity of inputs that contribute to CO<sub>2</sub> emissions.

**EQUATION 4.9(UNCHANGED)****CO<sub>2</sub> EMISSIONS FROM IRON & STEEL PRODUCTION (TIER 2)**

$$E_{CO_2, non-energy} = \left[ PC \cdot C_{PC} + \sum_a (COB_a \cdot C_a) + CI \cdot C_{CI} + L \cdot C_L + D \cdot C_D + CE \cdot C_{CE} + \sum_b (O_b \cdot C_b) + COG \cdot C_{COG} - S \cdot C_S - IP \cdot C_{IP} - BG \cdot C_{BG} \right] \cdot \frac{44}{12}$$

**EQUATION 4.10 (UNCHANGED)****CO<sub>2</sub> EMISSIONS FROM SINTER PRODUCTION (TIER 2)**

$$E_{CO_2, non-energy} = \left[ CBR \cdot C_{CBR} + COG \cdot C_{COG} + BG \cdot C_{BG} + \sum_a (PM_a \cdot C_a) - SOG \cdot C_{SOG} \right] \cdot \frac{44}{12}$$

Where, for iron and steel production:

$E_{CO_2, non-energy}$  = emissions of CO<sub>2</sub> to be reported in IPPU Sector, tonnes

PC = quantity of coke consumed in iron and steel production (not including sinter production), tonnes

COB<sub>a</sub> = 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<sub>b</sub> = quantity of other carbonaceous and process material *b*, consumed in iron and steel production, such as sinter or waste plastic, tonnes

COG = quantity of coke oven gas consumed in blast furnace in iron and steel production, m<sup>3</sup> (or other unit such as tonnes or GJ. Conversion of the unit should be consistent with Volume 2: Energy)

S = quantity of steel produced, tonnes

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

BG = quantity of blast furnace gas transferred offsite, m<sup>3</sup> (or other unit such as tonnes or GJ. Conversion of the unit should be consistent with Volume 2: Energy)

C<sub>x</sub> = carbon content of material input or output *x*, tonnes C/(unit for material *x*) [e.g., tonnes C/tonne]

Where, for sinter production:

$E_{CO_2, non-energy}$  = emissions of CO<sub>2</sub> to be reported in IPPU Sector, tonnes

CBR = quantity of purchased and onsite produced coke breeze used for sinter production, tonnes

COG = quantity of coke oven gas consumed in blast furnace in sinter production, m<sup>3</sup> (or other unit such as tonnes or GJ. Conversion of the unit should be consistent with Volume 2: Energy)

BG = quantity of blast furnace gas consumed in sinter production, m<sup>3</sup> (or other unit such as tonnes or GJ. Conversion of the unit should be consistent with Volume 2: Energy)

PM<sub>a</sub> = quantity of other process material *a*, other than those listed as separate terms, such as converter gas, natural gas and fuel oil, consumed for coke and sinter production in integrated coke production and iron and steel production facilities, tonnes

SOG = quantity of sinter off gas transferred offsite either to iron and steel production facilities or other facilities, m<sup>3</sup> (or other unit such as tonnes or GJ. Conversion of the unit should be consistent with Volume 2: Energy)

C<sub>x</sub> = carbon content of material input or output *x*, tonnes C/(unit for material *x*) [e.g., tonnes C/tonne]

## Second-order Draft

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.

Equation 4.11 calculates CO<sub>2</sub> emissions from production of direct reduced iron for the Tier 2 method based on fuel consumption and fuel carbon content. Emissions from DRI production are derived from combusting fuel, coke breeze, metallurgical coke or other carbonaceous materials, and are to be reported as IPPU emissions.

**EQUATION 4.11(UNCHANGED)****CO<sub>2</sub> EMISSIONS FROM DIRECT REDUCED IRON PRODUCTION (TIER 2)**

$$E_{CO_2, non-energy} = (DRI_{NG} \cdot C_{NG} + DRI_{BZ} \cdot C_{BZ} + DRI_{CK} \cdot C_{CK}) \cdot \frac{44}{12}$$

Where:

$E_{CO_2, non-energy}$  = emissions of CO<sub>2</sub> 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

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 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 iron and steel production is 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<sub>2</sub> emissions data are available from iron and steelmaking facilities, these data can be aggregated to account for national CO<sub>2</sub> emissions. If facility-specific CO<sub>2</sub> emissions data are not available, CO<sub>2</sub> emissions can be calculated from plant-specific activity data for individual reducing agents, exhaust gases, and other process materials and products. 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<sub>4</sub>**

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<sub>2</sub> above the charge, in the hood and off-gas channels, but some will remain un-reacted as CH<sub>4</sub> and non-methane volatile organic compounds (NMVOC). The amounts depend on the operation of the furnace. Sprinkle-charging will reduce the amounts of CH<sub>4</sub> compared to batch-wise charging. Increased temperature in the hood (less false air) will reduce the content of CH<sub>4</sub> further.

This section describes a Tier 1 default method and a more advanced Tier 3 facility-level method for CH<sub>4</sub> from sinter production or iron production, both of which are similar to the approaches described for estimating CO<sub>2</sub> emissions. There is no Tier 2 method. CH<sub>4</sub> may be emitted from steel-making processes as well, however those emissions are assumed to be negligible. Therefore, CH<sub>4</sub> emissions from steel-making processes are not discussed here.

Flaring of blast furnace gas and converter gas is a source of CH<sub>4</sub> emissions (and also N<sub>2</sub>O), potentially small, and therefore methodology is not provided.

**EQUATION 4.12 (UNCHANGED)**  
**CH<sub>4</sub> EMISSIONS FROM SINTER PRODUCTION (TIER 1)**  
 Sinter Production:  $E_{CH_4, non-energy} = SI \bullet EF_{SI}$

**EQUATION 4.13 (UNCHANGED)**  
**CH<sub>4</sub> EMISSIONS FROM BLAST FURNACE PRODUCTION OF PIG IRON (TIER 1)**  
 Pig Iron Production:  $E_{CH_4, non-energy} = PI \bullet EF_{PI}$

**EQUATION 4.14 (UNCHANGED)**  
**CH<sub>4</sub> EMISSIONS FROM DIRECT REDUCED IRON PRODUCTION (TIER 1)**  
 Direct Reduced Iron Production:  $E_{CH_4, non-energy} = DRI \bullet EF_{DRI}$

Where:

$E_{CH_4, non-energy}$  = emissions of CH<sub>4</sub> 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

$EF_x$  = emission factor, kg CH<sub>4</sub>/tonne  $x$  produced

The Tier 3 method uses plant specific emissions data. If actual measured CH<sub>4</sub> emissions data are available for coke production, these data can be aggregated to account for national CH<sub>4</sub> emissions. 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<sub>2</sub> and CH<sub>4</sub> to be used in Tier 1a, and discusses provision of carbon content to be used in carbon balances approaches at higher tiers.

#### TIER 1A METHOD

##### *Carbon dioxide emission factors*

Table 4.1 provides 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.

There are the two types of cokemaking process, with and without recovering the numerous chemical by-products. In non-recovering facilities, all of the coke oven gas is burned and, instead of recovery of chemicals, this process offers the potential for heat recovery and cogeneration of electricity. In this case all of the ovens are maintained under a negative pressure. Consequently, the ovens do not leak under normal operating conditions as do the by-product ovens which are maintained under a positive pressure. The combustion gases are removed from the ovens and directed to the stack through a waste heat tunnel that is located on top of the battery centreline and extends the length of the battery. The emission factor for non-recovery combustion stacks is much higher because all of the coke oven gas and all of the by-products are burned. In comparison, organic liquids (such as tar and light oil) are recovered at by-product recovery coke plants, and only about one third of the gas is consumed in underfiring the ovens. Table 4.1 includes average emission factors from stacks and quenching towers for non-recovery and recovery by-products, as well as the wide range of the European whose variability reflects the several mix of fuels used as primary fuel for coke production (including different combinations of coal, natural gas, fuel oil, coke oven gas, blast furnace gas and other fuels) plants.

Second-order Draft

<b>TABLE 4.1 (UPDATED)</b> <b>TIER 1 DEFAULT CO<sub>2</sub> EMISSION FACTORS FOR COKE PRODUCTION AND IRON&amp;STEEL PRODUCTION</b>		
Process	Emission Factors	Source
Coke production using By-product recovery technology tonne of CO <sub>2</sub> /tonne of coke	0.52 <sup>(1)</sup>	<p>Authors note: 0.52 tCO<sub>2</sub>/ t coke was chosen as the Tier 1 EF as a conservative factor, not comprising advanced energy saving technologies such as Coke Dry Quenching (CDQ), Coal moisture control and so on. In that case this EF can be lowered to 0,30 tCO<sub>2</sub>/ t coke according to experts judgement.</p> <p>USA: Emerging Technologies for Reducing GHG emissions from the Iron and Steel Industry (US EPA, Sep.2012) pg D-8, section D.2.5 GHG Emissions from Coke Plants: 0,21 tCO<sub>2</sub>/ t coke. Available at: <a href="https://www.epa.gov/sites/production/files/2015-12/document/ironsteel.pdf">https://www.epa.gov/sites/production/files/2015-12/document/ironsteel.pdf</a></p> <p>USA: Theoretical Minimum Energies to Produce Steel for selected conditions. Professor R.J. Fruehan et al, March 2000. pg 33 Table A-10. Minimum and Typical CO<sub>2</sub> Emissions in Cokemaking and Ore Agglomeration: 0,3-0,34 tCO<sub>2</sub> /t coke Available at: <a href="https://www.energy.gov/sites/prod/files/2013/11/f4/theoretical_minimum_energies.pdf">https://www.energy.gov/sites/prod/files/2013/11/f4/theoretical_minimum_energies.pdf</a></p> <p>China: 2009 value from “Determination of carbon dioxide emission factors in typical process for large iron-steel companies”. (Acta Scientiae Circumstantiae, Vol32 n08 Aug.2012 at China Academic Electronic Publishing House). page 2026 Table 4 The carbon emission factors of the typical processes: 0,518 tCO<sub>2</sub> /t coke. Available at: <a href="http://www.cnki.net">www.cnki.net</a></p> <p>Europe: JRC Reference Report "Best Available Techniques (BAT) Reference Document for Iron and Steel Production", Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control) 2013. Table 5.2: Input and output data from coke oven plants in different EU Member States from 2005 complemented by other references: 0,16-0,86 tCO<sub>2</sub>/t coke. Expert comment: This range of CO<sub>2</sub> varies because it depends on the kind of fuel gases used to fire the coke oven batteries. CO EF 200-4460 g CO/ t coke. Expert comment: CO emissions can be summed to this CO<sub>2</sub> EF because CO eventually oxides into CO<sub>2</sub>. Table 5.2 note: This range of CO varies because old plants with cracks in the oven walls (older than 20 years) emit more CO.</p> <p>So, in order to have an EU average CO<sub>2</sub> EF, CO and CO<sub>2</sub> emissions factors were summed<sup>(2)</sup>: 0,5103 tCO<sub>2</sub> / t coke for recent plants (up to 20 years) and 0,517 tCO<sub>2</sub> / t coke for older plants (more than 20 years).</p> <p>Available at: <a href="http://eippcb.jrc.ec.europa.eu/reference/BREF/IS_Adopted_03_2012.pdf">http://eippcb.jrc.ec.europa.eu/reference/BREF/IS_Adopted_03_2012.pdf</a> Europe benchmark: Official Journal of the European Union 17.05.2011, II (non-legislative acts) Available at: <a href="http://extwprlegs1.fao.org">http://extwprlegs1.fao.org</a> : 0,286 tCO<sub>2</sub>/ t coke</p>
Coke production using Non-recovery by-product	1.23	<p>Emerging Technologies for Reducing GHG emissions from the Iron and Steel Industry (US EPA, Sep.2012) pg D-9, section D.2.5 GHG Emissions from Coke Plants: 1.23 tCO<sub>2</sub>/t coke. This is the only publication about GHG in this type of technology route so far.</p>

616  
617  
618  
619  
620  
621  
622  
623

<b>TABLE 4.1 (UPDATED) (CONT.)</b> <b>TIER 1 DEFAULT CO<sub>2</sub> EMISSION FACTORS FOR COKE PRODUCTION AND IRON &amp; STEEL PRODUCTION</b>		
Sinter production (tonne of CO <sub>2</sub> /tonne of sinter)	0.23	<p>Authors note: 0.23 tCO<sub>2</sub>/ t sinter represents the average of the literature researched and refers to sinter plants which do not use carbonate ores. However, following European literature, for those sinter plants, which do use carbonate ores, than this CO<sub>2</sub> EF average can be up to twice as high. The CO<sub>2</sub> EF can vary widely due to the kind of fuel gases used in the ignition oven.</p> <p>USA: Theoretical Minimum Energies to Produce Steel for selected conditions. Professor R.J. Fruehan et al, March 2000. pg 33 Table A-10. Minimum and Typical CO<sub>2</sub> Emissions in Cokemaking and Ore Agglomeration: 0.17-0.19 tCO<sub>2</sub> /t sinter</p> <p>Available at:  <a href="https://www.energy.gov/sites/prod/files/2013/11/f4/theoretical_minimum_energies.pdf">https://www.energy.gov/sites/prod/files/2013/11/f4/theoretical_minimum_energies.pdf</a></p> <p>China: 2009 value from “Determination of carbon dioxide emission factors in typical process for large iron-steel companies”. (Acta Scientiae Circumstantiae, Vol32 n°08 Aug.2012 at China Academic Electronic Publishing House). page 2026 Table 4 The carbon emission factors of the typical processes: 0.21 tCO<sub>2</sub> /t sinter. Available at: <a href="http://www.cnki.net">www.cnki.net</a></p> <p>Europe: JRC Reference Report "Best Available Techniques (BAT) Reference Document for Iron and Steel Production", Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control) 2013. page 96 Table 3.4: Averaged maximum and minimum emissions concentrations in the sinter strand waste gas after abatement for sinter production in the EU-25 in 2004: 0.162-0.368 tCO<sub>2</sub>/t sinter and 8783-37000 g CO/ t sinter. Table 3.4 note on sinter plant CO<sub>2</sub> EF: Where carbonate iron ores are used, the concentration of CO<sub>2</sub> in the waste gas is increased, so that the application of EOS may strongly inhibit the sinter process. The CO<sub>2</sub> emissions in plants which do not use carbonate ores average from 161 to 368 kg/t sinter whereas in plants which do use carbonate ores the average can be up to twice as high. Expert comment: CO emissions can be summed to this CO<sub>2</sub> EF because CO eventually oxidizes into CO<sub>2</sub>. So, in order to have an EU average CO<sub>2</sub> EF, CO and CO<sub>2</sub> emissions factors were summed for EF provided without iron ore 0.17 – 0.405 tCO<sub>2</sub> / t sinter and a range for plant which do use iron ore was calculated based on the Table 3.4 comment 0.332 – 0.773 tCO<sub>2</sub> / t sinter <sup>(3)</sup>.</p> <p>Available at:  <a href="http://eippcb.jrc.ec.europa.eu/reference/BREF/IS_Adopted_03_2012.pdf">http://eippcb.jrc.ec.europa.eu/reference/BREF/IS_Adopted_03_2012.pdf</a></p> <p>Europe benchmark: Official Journal of the European Union 17.05.2011, II (non-legislative acts) Available at: <a href="http://extwprlegs1.fao.org">http://extwprlegs1.fao.org</a> – 0.171 tCO<sub>2</sub>/ t sinter</p>



Second-order Draft

<b>TABLE 4.1 (UPDATED) (CONT.)</b> <b>TIER 1 DEFAULT CO<sub>2</sub> EMISSION FACTORS FOR COKE PRODUCTION AND IRON &amp; STEEL PRODUCTION</b>		
Iron production (tonne CO <sub>2</sub> per tonne of hot metal)	1.41	<p>Authors note: 1.41 tCO<sub>2</sub>/ t iron produced (hot metal) represents the average of the literature researched and refers to blast furnaces and its secondary equipment operations (stoves and PCI plant).</p> <p>USA: Theoretical Minimum Energies to Produce Steel for selected conditions. Professor R.J. Fruehan et al, March 2000. pg 33 Table A-11. Comparison of Theoretical Minimum and Actual CO<sub>2</sub> Emissions for Selected Processes: 1.447-1.559 tCO<sub>2</sub> /t iron produced (hot metal) Available at: <a href="https://www.energy.gov/sites/prod/files/2013/11/f4/theoretical_minimum_energies.pdf">https://www.energy.gov/sites/prod/files/2013/11/f4/theoretical_minimum_energies.pdf</a></p> <p>China: 2009 value from “Determination of carbon dioxide emission factors in typical process for large iron-steel companies”. (Acta Scientiae Circumstantiae, Vol32 n°08 Aug.2012 at China Academic Electronic Publishing House). Page 2026 Table 4 The carbon emission factors of the typical processes: 1.375 tCO<sub>2</sub> /t iron produced (hot metal). Available at: <a href="http://www.cnki.net">www.cnki.net</a></p> <p>Europe: European IPPC Bureau (2001), Integrated Pollution Prevention and Control (IPPC) Best Available Techniques Reference Document on the Production of Iron and Steel, December 2001, Tables 7.2 and 7.3. Available at: <a href="http://eippcb.jrc.es/pages/FActivities.htm">http://eippcb.jrc.es/pages/FActivities.htm</a></p>
Direct Reduced Iron production (tonne CO <sub>2</sub> per tonne DRI produced)	0.70	<p>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. <a href="http://eippcb.jrc.es/pages/FActivities.htm">http://eippcb.jrc.es/pages/FActivities.htm</a></p>
Pellet production (tonne CO <sub>2</sub> per tonne pellet produced)	0.03	<p>Pellet 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 5.1 Page 95. <a href="http://eippcb.jrc.es/pages/FActivities.htm">http://eippcb.jrc.es/pages/FActivities.htm</a></p>

635  
636

TABLE 4.1 (CONT.) TIER 1 DEFAULT CO <sub>2</sub> EMISSION FACTORS FOR COKE PRODUCTION AND IRON & STEEL PRODUCTION		
Steelmaking Method		
Basic Oxygen Furnace (BOF) (tonne CO <sub>2</sub> per tonne of steel produced)	1.46	Steel Production: Consensus of experts and IISI Environmental Performance Indicators 2003 STEEL (International Iron and Steel Institute, 2004)
Basic Oxygen Furnace (BOF) (tonne CO <sub>2</sub> per tonne of steel produced)	1.39	Official journal of European Union , Average performance of 10% most efficient installation in EU for the year of 2007-2008. Annex1 PRODUCT BENCHMARKS, Table.1 Definition of product benchmark without consideration of exchangeability of fuel and electricity. “Benchmark value for steel industry under the EU-ETS“( May 2011)
Electric Arc Furnace (EAF) (tonne CO <sub>2</sub> per tonne of steel produced) **	0.08	Steel Production: Consensus of experts and IISI Environmental Performance Indicators 2003 STEEL (International Iron and Steel Institute, 2004)
Open Hearth Furnace (OHF) (tonne CO <sub>2</sub> per tonne of steel produced)	1.72	Steel Production: Consensus of experts and IISI Environmental Performance Indicators 2003 STEEL (International Iron and Steel Institute, 2004)
Global Average Factor (65% BOF, 30% EAF, 5% OHF)* (tonne CO <sub>2</sub> per tonne of steel produced)	1.06	Steel Production: Consensus of experts and IISI Environmental Performance Indicators 2003 STEEL (International Iron and Steel Institute, 2004)
<p>Note:</p> <ol style="list-style-type: none"> <li>(1) The average value from the literature range is used as default EF (0,510 tCO<sub>2</sub> /t coke). This is justified as the range is very wide based on the type of fuel gases used for firing oven batteries.</li> <li>(2) Note that these EF represent the sum of CO and CO<sub>2</sub> emissions, as CO oxidises and becomes CO<sub>2</sub></li> <li>(3) The average value from the literature range is used as default EF (0,265 tCO<sub>2</sub> /t sinter which do not use carbonate ores or 0.530 in plants which do use carbonate ores). This is justified as the range (0.16-0.37 tCO<sub>2</sub> / t sinter) is very wide based on the type of fuel gases used for ignition oven.</li> </ol> <p>* Factor based on 2003 international data where BOFs accounted for approximately 63 percent of world steel production and EAFs approximately 33 percent; OHF production accounted for the remaining 4 percent but is declining.</p> <p>** The emission factor for EAF steelmaking does not include emissions from iron production. The emission factors for BOF and OHF steelmaking do include emissions from blast furnace iron production.</p> <p>Note that the CO<sub>2</sub> emission factor for EAF steelmaking in this table is based on production of steel from scrap metal, and therefore the EAF emission factor does not account for any CO<sub>2</sub> emissions from blast furnace iron making. The Tier 1 CO<sub>2</sub> emission factor for EAFs in this table is therefore not applicable to EAFs that use pig iron as a raw material.</p>		

Second-order Draft

**Methane emission factors**

Default CH<sub>4</sub> emission factors are provided in Table 4.2 below.

<b>TABLE 4.2 (UPDATED)</b> <b>TIER 1 DEFAULT CH<sub>4</sub> EMISSION FACTORS FOR COKE PRODUCTION AND IRON&amp;STEEL PRODUCTION</b>		
<b>Process</b>	<b>Emission Factor</b>	<b>Source</b>
Coke Production (g CH <sub>4</sub> per tonne of coke produced)	1 – 80	Coke Production: JRC Reference Report, Best Available Techniques (BAT) Reference Document for Iron and Steel Production, Industrial Emissions Directive 2010/75/EU, Integrated Pollution Prevention and Control, 2013. Table 5.2
Sinter Production (kg per tonne of sinter produced)	0.07	EMEP/CORINAIR Emission Inventory Guidebook (EEA, 2005). Processes With Contact: <i>Sinter and Pelletizing Plants: Sinter and Pelletizing Plants (Except Combustion 030301)</i> Table 8.2a Emission factors for gaseous compounds
DRI Production kg /TJ (on a net calorific basis)	1	Energy Volume default emission factor for CH <sub>4</sub> Emissions from natural gas combustion. [See Table 2.3 of Volume 2, Chapter 2.]

**TIER 1B AND TIER 2 METHODS**

The default carbon contents in Table 4.3 should be used if there is not information on average country specific carbon content. Carbon contents in Table 4.3 are based on expert judgment, complemented with 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 a carbon balance approach at a 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 indicative of the processes and materials used at the facility. The Tier 3 method requires carbon contents and production/consumption mass rates for all of the 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 default factors 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&STEEL PRODUCTION (KG C/KG)**

Process Materials	Carbon Content
Blast Furnace Gas	0.243
Charcoal*	0.91
BF injection coal	0.806
Steam coal (combustion coal)	0.671
Coal Tar	0.924
Coke	0.888
Coke Oven Gas	0.228
Coking Coal	0.834
Direct Reduced Iron (DRI, Gas-base)	0.020
Direct Reduced Iron (DRI,Coal-based)	0.020
Dolomite/Crude dolomite	0.13
EAF Carbon Electrodes <sup>1</sup>	1.00
EAF coal	0.89
Heavy oil	0.793
Light oil	0.709
Kerosene	0.677
LPG	0.814
Hot Briquetted Iron <sup>2</sup>	0.02
Limestone	0.121
Natural Gas	0.549
Oxygen Steel Furnace Gas	0.412
Petroleum Coke <sup>2</sup>	0.87
Purchased Pig Iron	0.047
Scrap Iron <sup>2</sup>	0.04
Steel <sup>2</sup>	0.01

Note:

1 Assumed 80 percent petroleum coke and 20 percent coal tar

2 Source: table.4, page 13 of ISO14404-1 & ISO14404-2 with conversion from CO<sub>2</sub> to C (multiplied by 12/44).

\* The amount of CO<sub>2</sub> 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 lingots, 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<sub>2</sub> 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<sub>2</sub> emissions) or on plant-specific direct emissions monitoring data (for both CO<sub>2</sub> and CH<sub>4</sub> 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<sub>2</sub> 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**

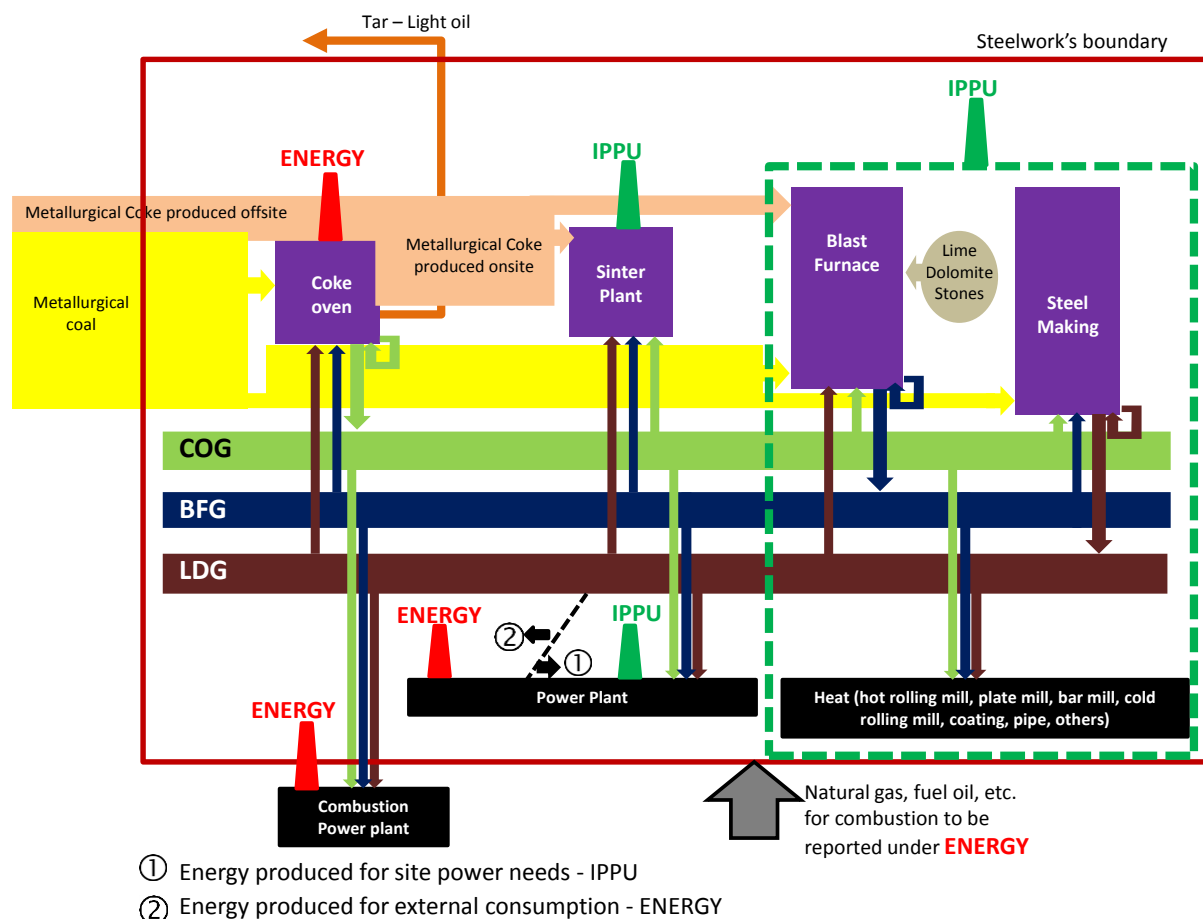
Iron and steel production consists of many production processes (facilities), such as coking, sintering, blast furnace, steelmaking, and rolling process. These processes are connected to each other by the pipeline network, which carries by-product gases, such as coke oven gas, blast furnace gas and basic oxygen furnace gas. This complexity creates risk of double counting and omission. Especially if there are many different types of steelworks in a particular country, it is difficult to calculate CO<sub>2</sub> emissions for the Energy Sector and the Industrial Processes Sector separately without any 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 a carbon balance at an iron and steelmaking facility to assure that CO<sub>2</sub> 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 criteria, 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 is shown in Figure 4.8a, according to:

- 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 mills, hot rolling mill, plate mill, bar mill, cold rolling mill, coating, pipe) should be reported under IPPU.
- The emissions from the combustion of blast furnace gas, coke oven gas and converter gas to produce electricity in an internal power plant, should be reported under:
  - Energy, if the electricity produced is exported offsite, which means to others facilities or if the electricity is sold to the grid.
  - IPPU, if the electricity is produced to cover the internal needs.
- The emissions from the combustion of blast furnace gas, coke oven gas and converter gas to produce heat in an internal unit, should be reported under:
  - Energy, if the heat produced is exported offsite, which means to others facilities.

- IPPU, if the heat is produced to cover the internal needs.
- The emissions from the combustion of blast furnace gas, coke oven gas and converter gas for metallurgical coke production should be reported under Energy.

**Figure 4.8a(new) Energy or IPPU CO<sub>2</sub> emissions allocation in an integrated iron and steel facility**



## RELATIONSHIP TO OTHER METHODOLOGICAL APPROACHES

In iron and steel industry, there has been a global effort to establish a common methodology for the calculation of CO<sub>2</sub> emissions and energy intensity of steelworks, and to conduct continuous data collection for tracking performance and for promoting international cooperation in CO<sub>2</sub> reduction. World Steel Association has established such method in 2007, and since then, has been conducting yearly CO<sub>2</sub> data collection of steelworks across the world with confidentiality. 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 good for CO<sub>2</sub> 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<sub>2</sub> emissions data (Reference ISO 14404 “Calculation method of carbon dioxide emission intensity from iron and steel production”). The net CO<sub>2</sub> emissions and production from a steel plant are calculated using all the parameters within the boundaries. The CO<sub>2</sub> emission intensity is calculated by the net CO<sub>2</sub> emission from the plant using the boundaries divided by the amount of crude steel production of that plant. With this methodology, the CO<sub>2</sub> emission intensity of steel plants is calculated irrespective of the type of process used, products manufactured and geographic characteristics. This calculation method only uses basic imports and exports 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 in the plant management. However, since different regions have different energy

## Second-order Draft

sources and raw materials available to them, the resulting calculations cannot be used to determine a benchmark for the free allocation under the emissions trading schemes, for example in Europe, or but it can be used for comparing performance of steel industry globally to know own position in energy and CO<sub>2</sub> efficiency.

There is a difference between 2019 Guidelines Refinement and ISO 14404 “Calculation method of carbon dioxide emission intensity from iron and steel production”, related with CO<sub>2</sub> emissions allocation between IPPU and Energy sectors, as in the last one the emissions from coking, sintering, blast furnace, direct reduction, making processes and reheating furnaces and rolling are reported under Energy, and only the emissions from the use of limestone and dolomite are reported under IPPU.

## OTHER FORMS OF CARBON

Although the dominant means of producing crude iron, or pig iron, is the blast furnace 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, these 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 vessels besides blast furnaces, often using natural gas or coal instead of coke, and these carbon sources should be accounted for in the same manner as coke because they are serving 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<sub>2</sub> and CH<sub>4</sub> emissions. If the coke fines are produced at a coke plant within the facility and the CO<sub>2</sub> and CH<sub>4</sub> emissions are accounted for in the coal entering the facility, or if the coke breeze is otherwise accounted for as purchased coke, the CO<sub>2</sub> and CH<sub>4</sub> 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 not to double count the use of blast-furnace-derived by-product gases such as blast furnace gas, or recovered converter off-gas<sup>1</sup> as energy in the energy sector as sources of CO<sub>2</sub>, 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 and 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 offsite. The process flow of exhaust gases are clearly illustrated in Figures 4.1-4.5.

The use of a default emission factor for CO<sub>2</sub> emission estimates with Tier 1a for metallurgical coke production and Tier 1 for iron and steel production, assumes an average mix of fuels use, between coke oven gas, blast furnace gas and in some cases the converter off-gas. On the other hand, the Tiers based on carbon balances approach considers a real flux of gases used and produced. Therefore, the combined used of Tier 1a to estimate CO<sub>2</sub> from metallurgical coke production and Tier 2 or 3 to estimate CO<sub>2</sub> from iron and steel production in integrated plants can lead to a double counting or an underestimation of some of the gases used. Similarly, the combined use of Tier 1 to estimate CO<sub>2</sub> from iron and steel production and Tier 2 or 3 to estimate CO<sub>2</sub> from metallurgical coke production can lead to a double counting or an underestimation of some of the gases used. The inventory compiler should take this situation in consideration when choose the Tiers to estimate CO<sub>2</sub> emissions from integrated iron and steel plants.

<sup>1</sup> Converter gas, usually named as BOF or LDG

**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<sub>2</sub> and CH<sub>4</sub> 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<sub>2</sub> or CH<sub>4</sub> emissions from this steelmaking process.

**OHF PROCESS**

Although the OHF is no longer prevalent, it may be necessary to inventory CO<sub>2</sub> and CH<sub>4</sub> 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**

[This section, 4.2.3, is an update/elaboration 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 default emission factors for coke production and iron and steel production used in Tier 1 may have an uncertainty of  $\pm 40$  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	Default Emission Factors	$\pm 40\%$
	National Production Data	$\pm 10\%$
	Material-Specific Default Carbon Contents	$\pm 10\%$
Tier 2	Material Country Specific Carbon Contents	$\pm 10\%$
	National Reducing Agent & Process Materials Data	$\pm 10\%$
Tier 3	Company-Derived Process Materials Data	$\pm 5\%$
	Company-Specific Measured CO <sub>2</sub> and CH <sub>4</sub> Data	$\pm 5\%$
	Company-Specific Emission Factors	$\pm 5\%$

For Tier 1 the most important type of activity data is the amount of steel produced using each method. National statistics should be available and likely have an uncertainty of  $\pm 10$  percent. For Tier 2, the total amount of reducing agents and process materials used for iron and steel production would likely be within 10 percent. Tier 3 requires plant-specific information on the amounts of reducing agents and process materials (about 5 percent uncertainty). Also actual emissions data for Tier 3 would be expected to have  $\pm 5$  percent uncertainty. Tier 3 uncertainty may be more accurately derived based on an analysis of the actual data received



Second-order Draft

858 **4.2.4 Quality Assurance/Quality Control (QA/QC),**  
859 **Reporting and Documentation**

860 No refinement

861

862

863 **4.3 FERROALLOY PRODUCTION**

864 No refinement

865

866

## 4.4 PRIMARY ALUMINIUM PRODUCTION

[This sub-chapter, 4.4, is an update/elaboration of 4.4 Chapter 4, Volume 3 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines) and should be used in conjunction with, where relevant, 4.4 Chapter 4, Volume 3 of the 2006 IPCC Guidelines]

### 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 refining technology<sup>1</sup>. A number of refinements and updates have been made to the 2006 IPCC Guidelines and are detailed in the following chapters.

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 (<6% 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 form, and configuration of the carbon anode and alumina feed system and are typically grouped by technology accordingly. In the 2006 guidelines, four technology types were defined, representing the technology in place at the time: Centre-Worked Prebake – *CWPB* (82% including Point-Fed Prebake, *PFPB*), Side-Worked Prebake – *SWPB* (2%), Horizontal Stud Søderberg – *HSS* (3%) and Vertical Stud Søderberg – *VSS* (13%).

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% share of global production in 2006 to >90% in 2017 but more significantly, the growth in technology without fully automated anode effect intervention strategies for perfluorocarbon (PFC) GHG emissions has risen from <30% in 2006 to >60% in 2017. As such, the technology types have been redefined as follows:

- (i) *Legacy Point-Fed Prebake (PFPB<sub>L</sub>)* – older cell designs with line currents of less than 350kA;
- (ii) *Modern Point-Fed Prebake (PFPB<sub>M</sub>)* – new cell technologies<sup>2</sup> 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<sub>MW</sub>)* – new cell technologies operating with large cells with line currents often in excess of 350kA, and with no automatic anode effect intervention capacity (refer to Box 4.1a description);
- (iv) *Side-Worked Prebake (SWPB)* technology;
- (v) *Horizontal Stud Søderberg (HSS)* technology; and
- (vi) *Vertical Stud Søderberg (VSS)* technology.

<sup>1</sup> 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.

<sup>2</sup> 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)

**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 generally employed in one technology class – *Modern Point-Fed Prebake without fully automated anode effect intervention strategies for PFC emissions (PFPB<sub>MW</sub>)* – where anode effects are terminated primarily through manual operator intervention, which can result in higher PFC emissions.

Although smelting technology has changed somewhat, the most significant process emissions have not. They are:

- (i) Carbon dioxide (CO<sub>2</sub>) 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 perfluorocarbons (PFCs) tetrafluoromethane (CF<sub>4</sub>) and hexafluoroethane (C<sub>2</sub>F<sub>6</sub>) 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: Carbon Monoxide (CO), Sulphur Dioxide (SO<sub>2</sub>), and Non-Methane Volatile Organic Carbon (NMVOC). Sulfur hexafluoride (SF<sub>6</sub>) is not emitted during the electrolytic process and is only rarely used when fluxing specialized, high magnesium aluminium alloys, from which small quantities can be released as fugitive emissions.

The decision tree in Figure 4.12 provides guidance for selecting a methodology estimating PFC emissions from aluminium production. All inventory compilers in countries with aluminium production should be able to implement 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. Aluminium smelters routinely collect the process data needed for calculation of Tier 2 emissions factors.

## **4.4.2 Methodological issues for primary aluminium production**

### **4.4.2.1 CHOICE OF METHOD FOR CO<sub>2</sub> EMISSIONS FROM PRIMARY ALUMINIUM PRODUCTION**

No refinement

### **4.4.2.2 CHOICE OF EMISSION FACTORS FOR CO<sub>2</sub> EMISSIONS FROM PRIMARY ALUMINIUM PRODUCTION**

No refinement

### 4.4.2.3 CHOICE OF METHOD FOR PFCs

#### 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. 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).

A low voltage anode effect (LVAE) is typically emission of PFC gases in cases where the cell voltage doesn't exceed the voltage threshold.

During electrolysis, alumina ( $\text{Al}_2\text{O}_3$ ) is dissolved in a fluoride melt comprising 80% by weight cryolite ( $\text{Na}_3\text{AlF}_6$ ). 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'. 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 Environmental Protection Agency & International Aluminium Institute 2008) for a period of around 3 seconds or more (Tabereaux 2004). These anode effects are now known as a high voltage anode effects (HVAE), which release both  $\text{CF}_4$  and  $\text{C}_2\text{F}_6$  emissions. Since the late 2000s, driven by the development of more productive, high amperage cell technology with many large anodes, low voltage anode effect (LVAE)  $\text{CF}_4$  emissions have been identified. These LVAE emissions have been the focus of much research and represent emissions generated as result of the same process upset condition but often at a smaller, localised scale. LVAE emissions have not been considered from the inventories to date, because the information was not available, but should now be included to ensure GHG inventories are as complete as possible. Therefore, reference should be made to *Total PFC emissions*, i.e. the sum of HVAE and LVAE emissions combined.

Both the Tier 2 and Tier 3 methods for HVAE PFCs are based on plant-specific process data for anode effects, which are regularly collected. In choosing a method for PFCs, it should be noted that the uncertainty associated with higher tier methodologies is significantly lower than that for Tier 1, and therefore Tier 2 and Tier 3 are strongly recommended if this is a *key category*. Depending on the production technology type, the uncertainty of the methods for PFCs ranges from several hundred percent for the Tier 1 method to less than twenty percent for the Tier 3 method. The Tier 3 methodology 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 routinely measure anode effect 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 the methods with reference to 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 best practice is to adopt the Tier 2 Slope method.

In the Tier 2 and Tier 3 methodology, LVAE PFC emissions are calculated by multiplying a technology specific factor, based on results from prior measurements, by the HVAE emissions (Marks & Nunez 2018b). This takes into account technology or plant specific performance at the HVAE level. There is currently no generally recognised means to calculate LVAE  $\text{CF}_4$  emissions from the process control data that is normally recorded during primary aluminium production as data related to LVAE are not typically included. The most accurate approach to date is to measure continuously both LVAE and HVAE PFC emissions, but this is not widely or regularly practiced to support inventory development. Moreover, there is currently no official methodology to standardise the measurement of LVAE PFC emissions at this time. 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.

The decision tree shown in Figure 4.12 describes *good practice* in choosing the PFC inventory methodology appropriate for national circumstances. For high performing facilities with low HVAE frequency, the Tier 3

method will likely not provide a significant improvement in the overall facility GHG inventory in comparison with the Tier 2 Method to estimate emissions from HVAE. However, the impact of LVAE emissions may still be significant and Tier 3 methods are recommended to correctly assess the GHG inventory of individual facilities. Consequently, it is *good practice* to identify these facilities prior to selecting methods in the interest of prioritising resources. The parameters that identify these high performing facilities depend on the type of process data collected by the facility. High performing facilities are those that operate with less than 0.02 anode effect minutes per cell day when anode effect minutes are measured. In addition, for these high performing facilities, accurate measurements of the Tier 3 HVAE PFC coefficient is difficult because the very low frequency of anode effects requires an extended time to obtain statistically robust results. The status of a facility as a high performing facility should be assessed annually because economic factors, such as the restarts of production lines after a period of inactivity, or process factors, such as periods of power curtailments, might cause temporary increases in anode effect frequency. In addition, over time, facilities that might not at first meet the requirements for high performers may become high performing facilities through implementation of new technology or improved work practices. Note that in all cases, applying different Tiers for different years will require careful implementation to ensure time series consistency.

For all other 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 Tier 2 and Tier 3 depending on the type of data available from individual facilities.

### **Tier 1 method for High Voltage Anode Effect (HVAE) emissions: Use of technology based default emission factors**

The Tier 1 method uses technology-based default emission factors for the main production technology types (Legacy PFPB, Modern PFPB, Modern PFPB<sub>MW</sub>, 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* only when PFCs from primary aluminium is not a *key category* and when pertinent process data are not available from operating facilities.

$$\begin{aligned} &\text{EQUATION 4.25 (UPDATED)} \\ &\text{HVAE PFC EMISSIONS (TIER 1 METHOD)} \\ &HVAE E_{CF_4,i} = \sum (HVAE EF_{CF_4,i} \bullet MP_i) \\ &\text{and} \\ &HVAE E_{C_2F_6} = \sum_i (HVAE EF_{C_2F_6,i} \bullet MP_i) \end{aligned}$$

Where:

HVAE E<sub>CF4</sub> = HVAE emissions of CF<sub>4</sub> from aluminium production, kg CF<sub>4</sub>

HVAE E<sub>C2F6</sub> = HVAE emissions of C<sub>2</sub>F<sub>6</sub> from aluminium production, kg C<sub>2</sub>F<sub>6</sub>

HVAE EF<sub>CF4,i</sub> = default HVAE emission factor by cell technology type *i* for CF<sub>4</sub>, kg CF<sub>4</sub>/tonne Al

HVAE EF<sub>C2F6,i</sub> = default HVAE emission factor by cell technology type *i* for C<sub>2</sub>F<sub>6</sub>, kg C<sub>2</sub>F<sub>6</sub>/tonne Al

MP<sub>i</sub> = metal production by cell technology type *i*, tonnes Al

### **Tier 1 method for Low Voltage Anode Effect (LVAE) emissions<sup>1</sup>**

The Tier 1 method for LVAE emissions uses technology-based default emission factors for the main production technology types (PFPB<sub>L</sub>, PFPB<sub>M</sub>, PFPB without automated controls, SWPB, VSS and HSS). PFC emissions can be calculated according to Equation 4.25a. The level of uncertainty in the Tier 1 method is much greater because

<sup>1</sup> C<sub>2</sub>F<sub>6</sub> emissions were not considered in the estimation of LVAE as C<sub>2</sub>F<sub>6</sub> 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<sub>2</sub>F<sub>6</sub> from LVAE does not occur, or occurs at level so low, it is considered negligible.

## Second-order Draft

individual facility HVAE performance, which is considered a proxy of overall process control, is not directly taken into account. Tier 1 can be consistent with *good practice* only when PFCs from primary aluminium is not a *key category* and when HVAE emissions data are not available from operating facilities.

**EQUATION 4.25A (NEW)**  
**LVAE PFC EMISSIONS (TIER 1 METHOD)**

$$LVAE E_{CF_4} = \sum [LVAE EF_{CF_4,i} * MP_i]$$

Where:

LVAE E<sub>CF<sub>4</sub></sub> = LVAE emissions of CF<sub>4</sub> from aluminium production, kg CF<sub>4</sub>

LVAE EF<sub>CF<sub>4</sub>,i</sub> = default LVAE emission factor by cell technology type *i* for CF<sub>4</sub>, kg CF<sub>4</sub>/tonne Al

MP<sub>i</sub> = metal production by cell technology type *i*, tonnes Al

**Tier 2a and Tier 3a methods for High Voltage Anode Effect (HVAE) emissions:  
Based on anode effect performance**

The equation for estimating individual plant HVAE CF<sub>4</sub> emissions is based on the relationship between anode effect emissions and performance. The slope coefficient is based on direct measurements of PFCs. Tier 2 makes use of weighted average coefficients from measurements at numerous facilities. Tier 3 is based on measurements at the individual facility (US Environmental Protection Agency & International Aluminium Institute 2008). Because the process mechanisms that produce PFC emissions during HVAE are similar for CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub>, the two gases should be considered together when estimating PFC emissions. C<sub>2</sub>F<sub>6</sub> emissions are calculated in all the HVAE methods described herein as a fraction of CF<sub>4</sub> 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, exclusively for the duration of the high voltage anode effect as depicted by the cell control system. 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).

**Slope Coefficient:** The coefficient characterises the kg of CF<sub>4</sub> per tonne of aluminium produced, divided by anode effect minutes per cell-day. 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<sub>4</sub> and C<sub>2</sub>F<sub>6</sub>.

**EQUATION 4.26 (UPDATED)**  
**HVAE PFC EMISSIONS BY SLOPE METHOD (TIER 2A AND TIER 3A METHODS)**

$$HVAE E_{CF_4} = S_{CF_4,i} \bullet AEM \bullet MP$$

*and*

$$HVAE E_{C_2F_6} = HVAE E_{CF_4} \bullet F_{C_2F_6/CF_4}$$

Where:

HVAE E<sub>CF<sub>4</sub></sub> = HVAE emissions of CF<sub>4</sub> from aluminium production, kg CF<sub>4</sub>

HVAE E<sub>C<sub>2</sub>F<sub>6</sub></sub> = HVAE emissions of C<sub>2</sub>F<sub>6</sub> from aluminium production, kg C<sub>2</sub>F<sub>6</sub>

S<sub>CF<sub>4</sub>,i</sub> = slope coefficient for CF<sub>4</sub> by cell technology type *i* (Tier 2A) or smelter specific emission ratio (Tier 3A) (kg CF<sub>4</sub>/tonne Al)/(AE-Mins/cell-day)

AEM = anode effect minutes per cell-day, AE-Mins/cell-day

MP = metal production, tonnes Al

$F_{C_2F_6/CF_4}$  = weight fraction of HVAE  $C_2F_6/CF_4$ , kg  $C_2F_6$ /kg  $CF_4$

**Overvoltage Coefficient:** Some process control systems characterize high voltage anode effects by calculating an Anode Effect Overvoltage<sup>1</sup> (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.

**EQUATION 4.27 (UNCHANGED)**

**HVAE PFC EMISSIONS BY OVERVOLTAGE METHOD (TIER 3 METHOD)**

$$E_{CF_4} = OVC \cdot \frac{AEO}{CE/100} \cdot MP$$

and

$$E_{C_2F_6} = E_{CF_4} \cdot F_{C_2F_6/CF_4}$$

Where:

$E_{CF_4}$  = HVAE emissions of  $CF_4$  from aluminium production, kg  $CF_4$

$E_{C_2F_6}$  = 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

$F_{C_2F_6/CF_4}$  = 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 measurement**

An alternative way to quantify PFC emissions from HVAE was proposed by (Marks & Nunez 2018a) and by (Dion *et al.* 2018a). This approach considers that the PFC generation rate is not linearly dependant of the duration of the HVAE. Therefore, PFCs are estimated for *each individual* HVAE (based on its duration) and the summation of individual HVAE emissions gives total HVAE emissions.

Tier 2b and 3b methods are considered particularly relevant 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 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 relatively large set of data collected in different facilities. Tier 3b methodology uses the same equations presented below with facility specific coefficients, based on the results of extensive gas monitoring measurement campaigns. A significant number of individual HVAE, with various durations, have to be monitored in order to obtain accurate coefficients.

<sup>1</sup> 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.



## Second-order Draft

The approach proposed by (Marks & Nunez 2018a) considers different emission rates based on individual anode effect durations (AED), as presented in Equation 4.27a; emission rate coefficients for Tier 2B are presented in Table 4.16a.

**EQUATION 4.27A (NEW)**  
**HVAE PFC EMISSIONS (TIER 2B AND TIER 3B METHOD – (MARKS & NUNEZ 2018A) )**

$$HVAE_{CF_4} = \sum_i [(K_1 \cdot AED_i^{K_2}) \cdot AED_i \cdot \frac{kA_i}{1000}]$$

Where:

HVAE<sub>CF<sub>4</sub></sub> = Total HVAE CF<sub>4</sub> produced during the considered period, as the sum of all individual 'i' HVAE emissions, kg CF<sub>4</sub>

AED<sub>i</sub> = Total duration of each individual 'i' HVAE, during which the cell voltage is above the HVAE detection threshold, s

kA<sub>i</sub> = Average line current during each individual 'i' HVAE, kA

K<sub>1</sub> = Emission rate coefficient dependant on the AED, dimensionless

K<sub>2</sub> = Emission rate coefficient dependant on the AED, dimensionless

The approach proposed by (Dion *et al.* 2018a) to quantify total CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub>, from the sum of emissions from individual HVAEs is presented in Equation 4.27b. Emission rate coefficient calculations are presented in Equation 4.27d.

**EQUATION 4.27B (NEW)**  
**HVAE PFC EMISSIONS (TIER 2B AND TIER 3B METHOD – (DION ET AL. 2018A) )**

$$HVAE_{CF_4} = \sum_i [(C_1 \cdot AED_i^{C_2}) \cdot MP]$$

$$HVAE_{C_2F_6} = \sum_i [(C_3 \cdot AED_i^{C_4}) \cdot MP]$$

Where :

HVAE<sub>CF<sub>4</sub></sub> = Total HVAE CF<sub>4</sub> produced during the considered period, as the sum of all individual HVAE emission, kg CF<sub>4</sub>

HVAE<sub>C<sub>2</sub>F<sub>6</sub></sub> = Total HVAE C<sub>2</sub>F<sub>6</sub> produced during the considered period, as the sum of all individual have emission, kg C<sub>2</sub>F<sub>6</sub>

AED<sub>i</sub> = Total duration of each individual 'i' HVAE during which the cell voltage is above the HVAE detection threshold, s

MP = Average daily metal production of the cell technology, tonnes Al

C<sub>1</sub> = Emission rate coefficient for CF<sub>4</sub> dependant on the metal production of the cell, tonnes Al.

C<sub>2</sub> = Emission rate coefficient for CF<sub>4</sub> dependant on the metal production of the cell, tonnes Al.

C<sub>3</sub> = Emission rate coefficient for C<sub>2</sub>F<sub>6</sub> dependant on the metal production of the cell, tonnes Al.

C<sub>4</sub> = Emission rate coefficient for C<sub>2</sub>F<sub>6</sub> dependant on the metal production of the cell, tonnes Al.

**BOX 4.2A (NEW)****HIGH VOLTAGE ANODE EFFECTS FOLLOWING START-UP OF ELECTROLYSIS CELLS**

From the moment when the anode beam is first moved, high voltage anode effects can occur during start-ups of electrolysis cells, 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). Even though some researchers (Kristensen *et al.* 2007; Reny *et al.* 2016) have demonstrated the possibility of having cell start-ups without HVAE, it is not a common practice and PFC emissions from cell start-ups may be a significant fraction of the smelters total PFC during certain periods, especially when the aluminium smelter is annually carrying out a large number of cell start-ups.

HVAE PFC emissions measured during cell start-up events have demonstrated lower emission factors than during normal operations. For this reason, accounting for these HVAEs using the standard emission factor from the facility (Tier 3a) or technology class (Tier 2a) may lead to overestimation of these PFC emissions (Dando *et al.* 2008; Xu *et al.* 2008; Maltais *et al.* 2010).

To take into consideration the different process dynamics of HVAEs during the start-up of cells, use of the proposed Tier 2b non-linear approach from Equation 4.27 (A or B) would lead to more correct quantification of these PFC emissions when no specific measurement data are available.

When data are available, it is good practice to determine a specific Tier 3 coefficient based on the total emissions of PFC per cell start-up of the facility.

$$E_{CF_4} = (EF_{CSU} \bullet N_{CSU})$$

Where:

$E_{CF_4}$  = Total amount of  $CF_4$  produced during start-ups for a specific period, kg  $CF_4$

$EF_{CSU}$  = Average amount of  $CF_4$  produced during the cell start-up period, kg  $CF_4$ / Cell start-up.

$N_{CSU}$  = Total number of cell start-ups during the specific period considered, Cell start-up

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). Such modification to the detection threshold should be specific to each facility, based on historical data.

**Tier 2 and Tier 3 method for Low Voltage Anode Effect (LVAE) emissions**

The Tier 2 method for LVAE emissions uses a technology-based default emissions ratio, while the Tier 3 method uses a facility-specific emissions ratio. The equation for estimating LVAE  $CF_4$  emissions is based on the HVAE PFCs, which is considered a proxy for performance and process control. The ratios are based on direct measurements of PFCs (Marks & Nunez 2018b). Tier 2 makes use of average or median ratios from measurements at a number of facilities. The median is used for select technology classes where the weighted average was skewed due to a small number of very high LVAE/HVAE ratios in the dataset which were reflective of unusual conditions e.g. start up. Tier 3 is based on measurements at the individual facility. During LVAE, the cell voltage typically remains below the formation voltage of  $C_2F_6$ . In some instances, where cell voltage is elevated above typical 'background' levels but below the 8V threshold, some  $C_2F_6$  can be generated (Wong & Marks 2013). At present however,  $C_2F_6$  emissions are not calculated in the LVAE methods described and are considered negligible emissions.

**EQUATION 4.27C (NEW)****LVAE PFC EMISSIONS (TIER 2 AND TIER 3 METHODS)**

$$LVAE\_E_{CF_4} = \sum (HVAE\_E_{CF_4,i} * ER_{LV\ CF_4,i} * MP_i)$$

Where:

$LVAE\_E_{CF_4}$  = low voltage anode effect emissions of  $CF_4$  from aluminium production, kg  $CF_4$

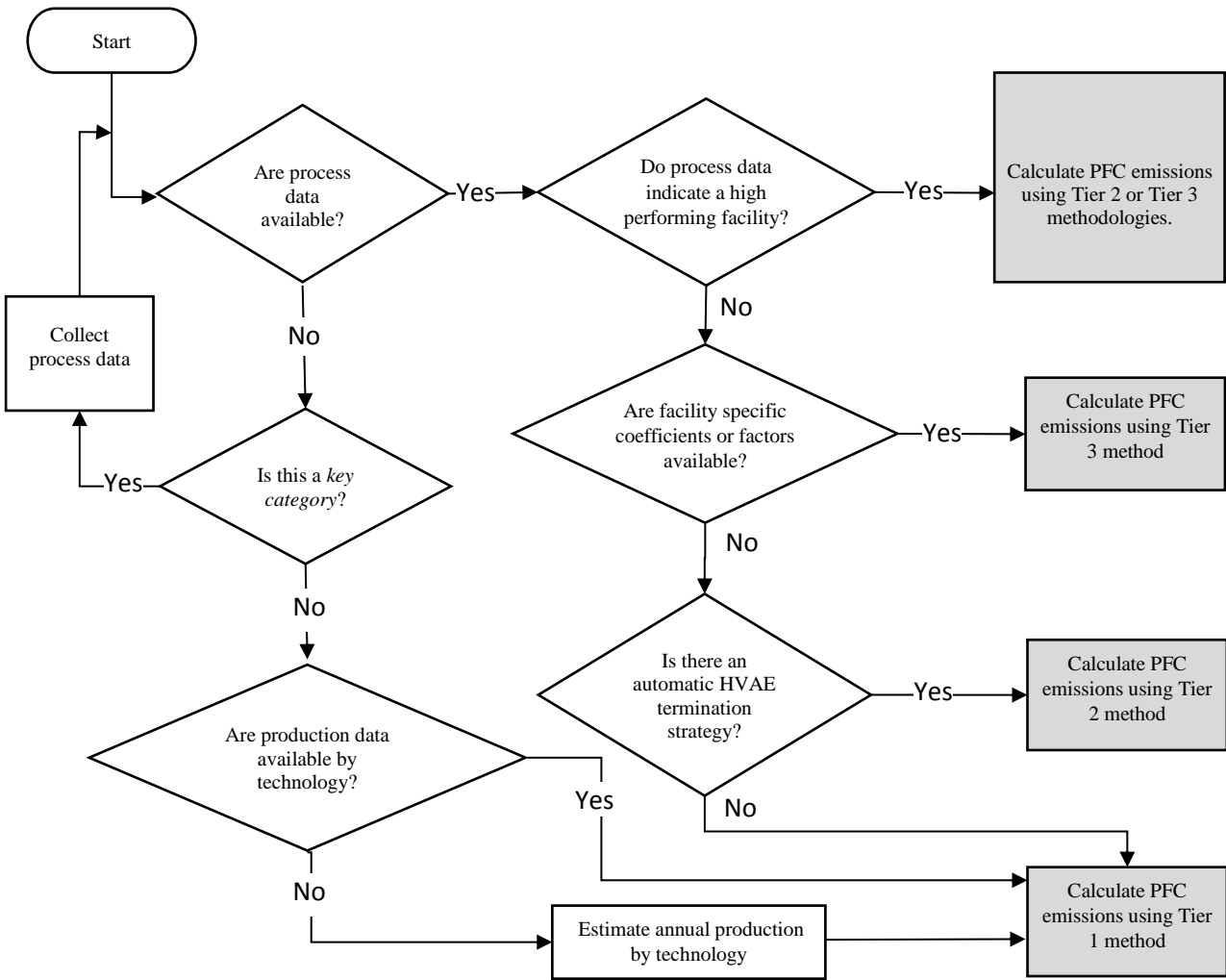
Second-order Draft

HVAE<sub>ECF4</sub> = high voltage anode effect emissions of CF<sub>4</sub> from aluminium production by cell technology *i*, kg CF<sub>4</sub>

ER<sub>LV CF4</sub> = Ratio of LVAE/HVAE CF<sub>4</sub> emissions, either default ratio by cell technology type *i* (Tier 2) or smelter specific emission ratio (Tier 3)

MP = metal production by cell technology type *i*, tonnes Al.

**Figure 4.12 (updated) Decision tree for calculation of PFC emissions from primary aluminium production**



#### 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 4.25a). Aluminium production data by technology is usually available through national statistics publications or through publicly available company reports and websites.

<b>TABLE 4.15 (UPDATED)</b> <b>TECHNOLOGY SPECIFIC DEFAULT EMISSION FACTORS FOR THE CALCULATION OF HVAE AND LVAE EMISSIONS FROM ALUMINIUM PRODUCTION (TIER 1 METHOD) (MARKS &amp; NUNEZ 2018B)</b>						
Technology	HVAE				LVAE	
	CF <sub>4</sub>		C <sub>2</sub> F <sub>6</sub>		CF <sub>4</sub>	
	EF <sub>CF4</sub> (kg/tonne Al)	Uncertainty Range (%) <sup>b</sup>	EF <sub>C2F6</sub> (kg/tonne Al)	Uncertainty Range (%)	EF <sub>CF4</sub> (kg/tonne Al)	Uncertainty Range (%)
PFPB <sub>L</sub>	0.029	-88/+234	0.001	-93/+208	0.016	+936/-85
PFPB <sub>M</sub>	0.030	-88/+226	0.001	-91/+217	0.018	+247/-98
PFPB <sub>MW</sub>	0.161 <sup>a</sup>	-85/+476	0.005 <sup>a</sup>	-98/+478	-	-
SWPB	0.391	-76/116	0.093	-89/+68	0.010	+69/-69
VSS	0.210	95/+447	0.011	-95/+412	0.001	+61/-52
HSS	0.503	-79/+112	0.033	-76/+86	0.026	- <sup>b</sup>
Notes: <sup>a</sup> includes LVAE emissions <sup>b</sup> single data point – no uncertainty calculated.						

Second-order Draft

## Tier 2a: HVAE-PFC emission factor based on technology specific relationship between 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 <sup>1</sup> METHODOLOGY (TIER 2A METHOD) (MARKS & NUNEZ 2018B)				
Technology	CF <sub>4</sub>		Weight Fraction C <sub>2</sub> F <sub>6</sub> /CF <sub>4</sub>	
	SC <sub>CF4</sub> (kg CF <sub>4</sub> /tonne Al)/(AE-Mins/cell-day) <sup>a</sup>	Uncertainty Range (%)	C <sub>2</sub> F <sub>6</sub> /CF <sub>4</sub>	Uncertainty (%)
PFPB <sub>L</sub>	0.127	-33/+58	0.114	-72/+174
PFPB <sub>M</sub>	0.104	-27/+32	0.057	-55/+55
PFPB <sub>MW</sub> <sup>a</sup>	-	-	-	-
SWPB	0.233	-27/+44	0.280	-55/+58
VSS	0.060	-54/+123	0.093	-78/+210
HSS	0.165	-47/+28	0.077	-61/+48
Note: <sup>a</sup> Tier 2 default coefficients are not available for Modern PFPB Technology 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

The Tier 2b method proposed by (Marks & Nunez 2018a) (Equation 4.27A) uses different emission rate coefficients to estimate HVAE emissions, based on the anode effect duration (AED) of individual high voltage anode effects, as listed below in Table 4.16a.

TABLE 4.16A (NEW) SPECIFIC HAVE-PFC EMISSION RATE COEFFICIENTS BASED ON THE ANODE EFFECT DURATION AS CALCULATED BY (MARKS & NUNEZ 2018A) (TIER 2B METHOD).		
AED <sup>a</sup>	Value of K <sub>1</sub>	Value of K <sub>2</sub>
1s < AED ≤ 5s	0.0341	-0.244
6s < AED ≤ 200s	0.0473	-0.307
AED > 200 s	0.1661	-0.521
<sup>a</sup> In the rare occurrences where AED is equivalent to 0s, the equation that should be used is: kg CF <sub>4</sub> = 0.576 · kA		

For the Tier 2b method proposed by (Dion *et al.* 2018a) to calculate HVAE emissions (Equation 4.27b), emission rate coefficients C<sub>1</sub>, C<sub>2</sub>, C<sub>3</sub> and C<sub>4</sub> are defined in Equation 4.27d below for the generic smelter, based on the daily metal production per cell.

<sup>1</sup> 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 4.27D (NEW)**  
**EMISSION RATE COEFFICIENTS FOR HVAE PFC (TIER 2B METHOD – (DION *ET AL.* 2018A) )**

$$C_1 = 0.6415 \bullet MP + 5.878$$

$$C_2 = -0.0972 \bullet MP + 0.8905$$

$$C_3 = 0.238MP^2 - 1.407 \bullet MP + 2.342$$

$$C_4 = -0.0981MP^2 + 0.381 \bullet MP + 0.3413$$

Where :

$C_1$  = Emission rate coefficient for  $CF_4$  dependant on the metal production of the cell, tonnes Al.

$C_2$  = Emission rate coefficient for  $CF_4$  dependant on the metal production of the cell, tonnes Al.

$C_3$  = Emission rate coefficient for  $C_2F_6$  dependant on the metal production of the cell, tonnes Al.

$C_4$  = Emission rate coefficient for  $C_2F_6$  dependant on the metal production of the cell, tonnes Al.

MP = Average daily metal production of the cell technology, tonnes Al

**Tier 2: LVAE-PFC emission factor based on technology specific relationship between anode effect performance and PFC emissions**

The Tier 2 LVAE emissions ratio method is based on technology specific ratios for the applicable reduction cell and process control technology as listed in Table 4.16b. Median ratios are recommended for PFPB technologies as very high LVAE/HVAE ratios in the measurement dataset skewed the average ratio significantly.

**TABLE 4.16B (NEW)**  
**TECHNOLOGY SPECIFIC DEFAULT EMISSION FACTORS FOR THE CALCULATION OF LVAE PFC EMISSIONS FROM ALUMINIUM PRODUCTION (TIER 2 METHOD) (MARKS & NUNEZ 2018B)**

Technology	Emissions Ratio of LVAE/HVAE	Uncertainty (%)
	<b>ER<sub>CF4</sub></b>	
PFPB <sub>L</sub>	0.400 <sup>a</sup>	+431/-98
PFPB <sub>M</sub>	0.752 <sup>a</sup>	+311/-99
PFPB <sub>MW</sub>	-	-
SWPB	0.104	+86/-86
VSS	0.058	+157/-95
HSS	0.054	- <sup>b</sup>

Note:

<sup>a</sup> median value is used for default ratios due to outliers skewing weighted average.

<sup>b</sup> single data point – no uncertainty calculated.

**Tier 3: PFC emission factors based on a facility specific relationship between anode effect performance and PFC emissions**

The Tier 3 method is based on facility-specific coefficients. These coefficients characterize the relationship between facility anode effect performance and measured PFC emissions from periodic or continuous measurements that are consistent with established measurement practices (US Environmental Protection Agency & International Aluminium Institute 2008). For LVAE, facility-specific ratios can be established based on direct measurement of HVAE and LVAE for a period of time.

#### 1293 4.4.2.5 CHOICE OF ACTIVITY DATA

1294 Production statistics should be available from every facility to enable use of Tier 1 methods for both CO<sub>2</sub> and PFC  
1295 emissions. Uncertainty in the tonnes of aluminium produced is likely to be low in most countries. Given the  
1296 expected universal availability of production data, production capacity data should only be used as a check on  
1297 production statistics.

1298 *Good practice* methods for PFC emissions resulting from high voltage anode effects require accurate high voltage  
1299 anode effect minutes per cell day data for all cell types. Annual statistics should be based on the production-  
1300 weighted average of monthly high voltage anode effect data. Both Tier 2 and Tier 3 utilize high voltage anode  
1301 effect minutes per cell day and aluminium production data.

1302 *Good practice* methods for PFC emissions resulting from low voltage anode effects only require accurate  
1303 aluminium production data for Tier 1. For 2 and Tier 3 methods, *good practice* methods for HVAE should be  
1304 adopted as these are used in the calculation of LVAE emissions.

1305 Individual aluminium companies or industry groups, national aluminium associations or the International  
1306 Aluminium Institute, should be consulted to ensure that the data are available and in a useable format for inventory  
1307 estimation.

1308 For CO<sub>2</sub> emissions, all aluminium smelters collect data to support Tier 2 or Tier 3 methods. Söderberg smelters  
1309 collect anode paste consumption data while Prebake smelters record baked anode consumption. The Tier 2 and  
1310 Tier 3 methods use the same equation for calculation of CO<sub>2</sub> emissions; however, the Tier 3 method uses facility  
1311 specific composition data for anode materials while the Tier 2 method uses industry average anode composition  
1312 data.

#### 1313 4.4.2.6 COMPLETENESS

1314 No refinement

#### 1315 4.4.2.7 DEVELOPING A CONSISTENT TIME SERIES

##### 1316 PFC EMISSIONS RESULTING FROM HIGH VOLTAGE ANODE EFFECTS

1317 A complete time series of PFC related activity data such as high voltage anode effect (HVAE) minutes per cell  
1318 day or overvoltage gives the best time series results. Because PFC emissions only became a major focus area in  
1319 the early 1990s for the global aluminium industry, some facilities may have limited information about the required  
1320 anode effect data to implement Tier 2 or Tier 3 PFC inventory practices over the entire time covered by the  
1321 inventory. Substantial errors and discontinuities can be introduced by reverting to Tier 1 methods for PFC  
1322 emissions for years for which activity data are not available. The appropriateness of applying Tier 2 or Tier 3 PFC  
1323 emission factors back in time to a given facility and availability of detailed process data vary with the specific  
1324 conditions. Generally, backcasting of Tier 2 or Tier 3 methods using splicing or surrogate data are preferred over  
1325 use of Tier 1 emission factors. Specifically, where only high voltage anode effect frequency data are available and  
1326 high voltage anode effect duration data are unavailable, it is *good practice* to splice or backcast PFC emissions per  
1327 tonne aluminium based on high voltage anode effect frequency data. When going back in time using Tier 2  
1328 methodologies, it is important to take into consideration the reported change in slope coefficient for high voltage  
1329 anode effects. Hence, it is suggested that inventory compilers use the respective emission factors from the 2006  
1330 *IPCC Guidelines* for annual inventories up to 2018 with any of the two suggested methods. However, for the year  
1331 2019 and up, good practices are to use the slope model, with the emission factors reported in the 2019 *Refinement*  
1332 for quantification of PFC using Tier 2.

1333 Inventory compilers switching from the Tier 3 overvoltage methodology to the Tier 3 slope model should use both  
1334 methods in parallel for a period of three years to evaluate the potential impact. However, publications demonstrated  
1335 that the difference between both methods should be negligible with Tier 3 emission factors (Dion et al. 2017;  
1336 Marks & Bayliss 2012). If the difference between both methods is greater than 5% over the transition period, then  
1337 good practices would require contacting the international aluminum institute for expert advice to determine the  
1338 optimal course of action for the best representativeness.

1339 Currently many facilities are making PFC measurements that facilitate implementation of Tier 3 PFC inventory  
1340 methods. There are a number of issues that impact on whether Tier 3 PFC emission factors can be extrapolated to  
1341 past inventory periods. Factors that should be considered include whether any technology upgrades have been  
1342 implemented at the facility, including significant amperage increase or new cell control system, whether there have  
1343 been substantial changes in work practices affecting the distribution of the anode effect durations, whether any  
1344 changes in the calculation of underlying process data have occurred, and the quality of the measurements made to

establish the Tier 3 factor. 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.

## **PFC EMISSIONS RESULTING FROM LOW VOLTAGE ANODE EFFECTS**

Low voltage anode effects (LVAEs) became a concern for the aluminum 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). Actual data indicates that these PFC emissions are greater for specific cell technologies, usually with cell amperage higher than 350kA. Therefore, inventory compilers are encouraged to backcast the LVAE PFC emissions, for national inventories, by using the respective Tier 2 coefficient specific to each category up to 2007. If Tier 3 coefficients are available, it is suggested that those be used for the corresponding years of operations. There are several issues that impact on whether Tier 3 PFC emission factors can be extrapolated to past inventory periods. Factors that should be considered were presented in the previous section on high voltage anode effects, however, change in the alumina feeding strategy should also be considered as it can significantly impact the LVAE emission coefficient. Finally, the study performed by Dion *et al.* highlighted the importance of considering numerous facilities when estimating LVAE emissions using Tier 2 emission factors (Dion *et al.* 2018b) thus, back casting for a limited number of smelters should be avoided using Tier 2 coefficients. This issue is driven by the high uncertainty of LVAE PFC emissions from individual smelters and the possible variability of these emissions related to change in the control process of the electrolysis cells. Henceforth, for individual smelters inventories and historical data, the bias associated to the omission of LVAE emissions is preferable to the use of Tier 2 coefficients as it could lead to important overestimations (Dion *et al.* 2018b).

## **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**

The uncertainty in the emission factors for calculating carbon dioxide emissions from carbon anode or paste consumption should be less than  $\pm 5$  percent for both the Tier 2 and Tier 3 methods, and less than  $\pm 10$  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 Söderberg 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.



## Second-order Draft

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. The high level of uncertainty in the Tier 1 method results directly from the large variability in anode effect performance among operators using similar production technology, and the relative contribution of LVAE emissions to total emissions. 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 method over the Tier 2 method for estimating HVAE; however, the level of uncertainty reduction depends on the cell technology type. The uncertainty for industry slope coefficients for individual facilities ranges from -27 to +32 percent for Modern PFPB, to -54 to +123 percent for VSS. Both Tier 2 and Tier 3 methods are based on direct PFC measurements that establish a relationship between anode effect performance and PFC specific emissions. The Tier 2 method uses an industry average equation coefficient while the Tier 3 method uses a facility specific coefficient 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 3 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). When properly established these Tier 3 coefficients will have an uncertainty of +/-15 percent at the time the coefficients are measured.

The level of uncertainty to estimate LVAE emissions from Tier 2 and Tier 3 methods is more important than HVAE emissions estimations. The level of emissions is dependent on numerous factors and there is no clear correlation within the industry which leads to the high variability observed between different facilities. The lowest uncertainty for LVAE estimations is from Tier 3 PFC calculations. However, taking into consideration the lower concentration of this type of emission and the detection limit of the measuring instrument, it is expected that the uncertainty will still be more important than that of the HVAE tier 3 methods.

#### 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. The other component of calculated facility specific emissions using Tier 2 or Tier 3 methods is the anode effect activity data, i.e., anode effect minutes per cell day. 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.

### 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 Söderberg 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<sub>2</sub> 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 high voltage anode effect emissions from primary aluminium, the EPA/IAI Protocol for Measurement of Tetrafluoromethane (CF<sub>4</sub>) and Hexafluoroethane (C<sub>2</sub>F<sub>6</sub>) Emissions from Primary Aluminum Production is the internationally recognized standard (US Environmental Protection Agency & International Aluminium Institute 2008). Significant differences between calculated coefficients based on PFC measurements and the industry average Tier 2 coefficients for similar reduction technology should elicit further review and checks on calculations. Large differences should be explained and documented. An international data set of anode effect performance, which can be used to identify outlier data, is available from the International Aluminium Institute (IAI). 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 low voltage anode effect 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<sup>1</sup> 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<sub>4</sub> and C<sub>2</sub>F<sub>6</sub> 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.

---

<sup>1</sup> Reference to PFCs from this section applies to both HVAE and LVAE emissions.

Second-order Draft

<b>TABLE 4.17 (UPDATED)</b> <b>GOOD PRACTICE REPORTING INFORMATION FOR CALCULATING CO<sub>2</sub> AND PFC EMISSIONS FROM ALUMINIUM PRODUCTION BY TIER</b>			
<b>Data</b>	<b>Tier 3</b>	<b>Tier 2</b>	<b>Tier 1</b>
<b>PFCs</b>			
Annual national production (by technology)			X
Annual production by smelter (by technology)	X	X	
Anode Effect minutes per cell-day	X	X	
Anode Effect Overvoltage (mV)	X		
Facility specific emission coefficients linked to anode effect performance	X		
Technology specific emission coefficients linked to anode effect performance		X	
Default technology emission coefficients			X
Supporting documentation	X	X	X
<b>CO<sub>2</sub></b>			
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		

1490

1491

1492

## 4.4.5 Methodological issues for alumina production

[Sections 4.4.5 to 4.4.7 provides entirely *new guidance* relating to greenhouse gas (GHG) emissions from alternative processes for alumina production, as part of the *2019 Refinement* to the *2006 IPCC Guidelines*. It follows on from Section 4.4.4 in Chapter 4, Volume 3 of the *2006 IPCC Guidelines*].

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 lime production (Volume 3, Section 2.3) and fossil fuel combustion (Volume 2, Chapter 2).

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 4.12a).

### 4.4.5.1 ALTERNATIVE ALUMINA REFINING PROCESSES

#### BAYER-SINTERING PROCESS

In 2017, an estimated 4% of alumina produced globally was via the 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<sub>2</sub>O<sub>3</sub>), which is the basic raw material for primary aluminium production.

Depending on bauxite quality there are 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%) is processed in the sintering branch and the rest is effectively processed by the conventional Bayer process (Figure 4.12a). 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<sub>2</sub>, NO<sub>2</sub> and CH<sub>4</sub> from the Bayer-sintering process are listed below, of which, the sintering step is the main focus of this section:

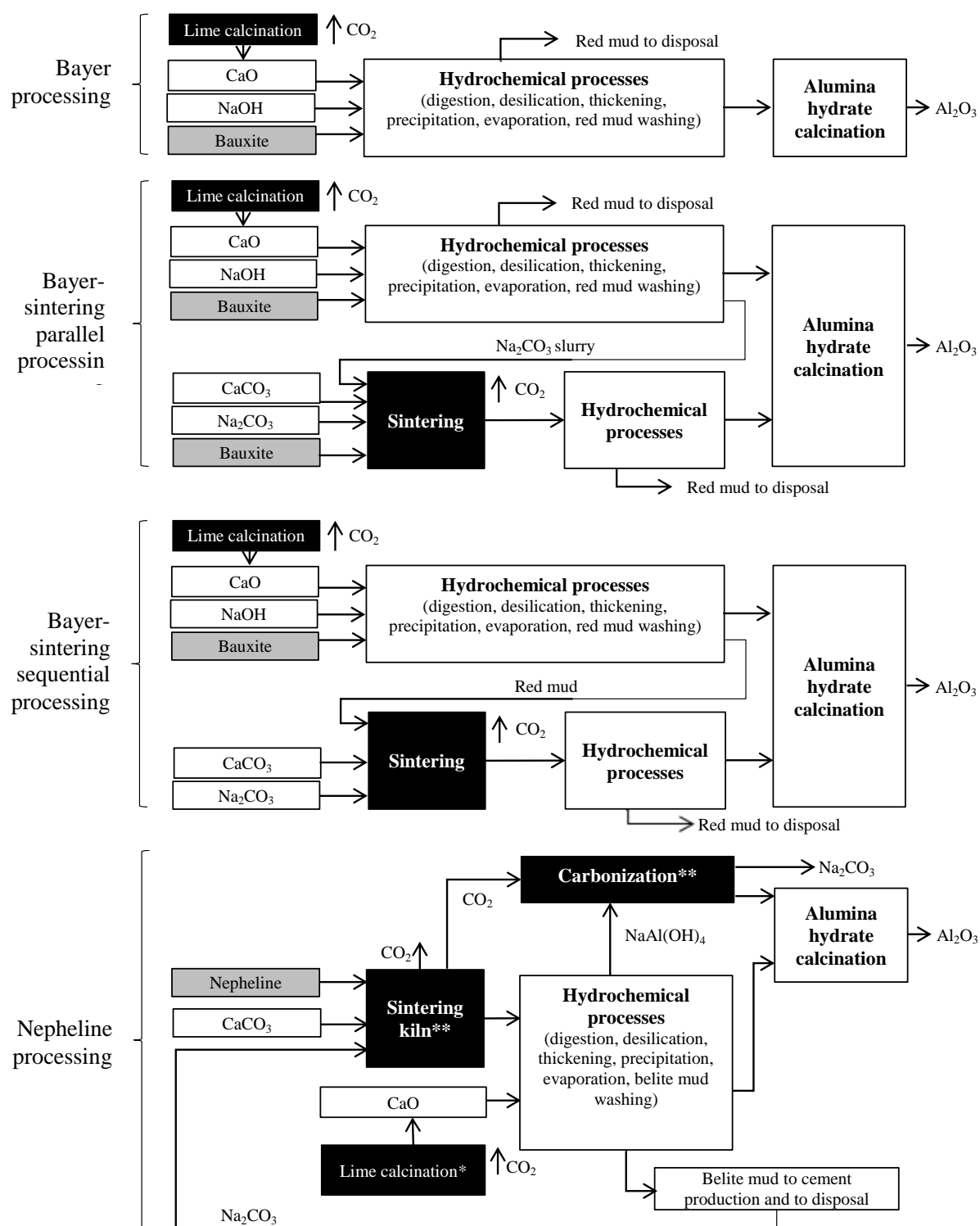
- Sintering (fuel combustion<sup>1</sup> and carbonates decomposition)<sup>2</sup>
- Power and heat production facilities (fuel combustion)<sup>1</sup>
- Alumina hydrate calcination (fuel combustion)<sup>1</sup>
- Lime calcination (fuel combustion and carbonates decomposition)<sup>3</sup>.

<sup>1</sup> Calculation of GHG emissions shall be done in accordance to Volume 2 Energy, Chapter 2 Stationary combustion for fuel burning.

<sup>2</sup> Emissions from carbonate decomposition shall be calculated in accordance to Section 4.4.5.2 of current Chapter.

<sup>3</sup> 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.

Second-order Draft

**Figure 4.12a (new)     Alumina production processes**

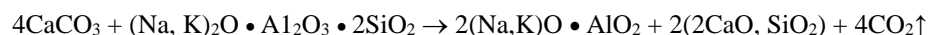
\* Calculated in accordance to Volume 3 Industrial Processes and Product Use, Chapter 2 Mineral industry emissions, Section 2.3 Lime production.

\*\* 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% of global production<sup>1</sup> 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 aluminosilicate that contains more silica than alumina. In order to make silica insoluble at the leaching process, it is combined with lime forming  $2\text{CaO} \cdot \text{SiO}_2$  (belite) using the sintering process. The belite mud is used in the cement production whereas sodium and potassium streams are used to produce soda ash and potash assuring complex processing of nepheline raw material.

The main steps in the process are (refer to Figure 4.12a): 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  $\text{CO}_2$ :



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  $\text{CO}_2$  in the process (Figure 4.12a).

Pure alumina hydrate is passed through a rotary or fluidised bed calciner (FBC) at 1100°C to drive off the chemically combined water.

The main sources of greenhouse gases emissions from the nepheline process are similar to the Bayer-sintering process but since there are many by-products produced alongside alumina (i.e. belite mud for cement, soda ash, potash), the emissions of  $\text{CO}_2$  shall be split between output products.

## OTHER GHG SOURCES AND CAPTURE

$\text{CO}_2$  and  $\text{CH}_4$  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%, from expert opinion).

Examples of such sub-processes include:

- Flue gas desulphurization
- Acid cleaning of process equipment
- Organic carbon in bauxite
- Liquor burning

There are also a number of  $\text{CO}_2$  capture pathways to consider:

- Carbonization
- $\text{CO}_2$  absorption through use of bauxite residue for flue gas desulphurization
- $\text{CO}_2$  absorption through use of water collected from bauxite/nepheline storage residue area.

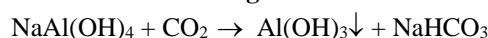
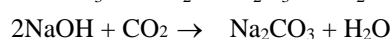
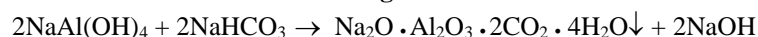
As noted throughout Volume 3 on Industrial Processes and Product Use (IPPU), the emission estimation methodologies outlined in this Chapter consider only process-related emissions and do not consider energy-related emissions. Inventory compilers should ensure that energy-related emissions are accounted 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  $\text{CO}_2$  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.

<sup>1</sup> There is only a single alumina refinery globally that uses this technology (Russian Federation) and estimate is based on its annual production as a proportion of total global alumina production.

Second-order Draft

***CO<sub>2</sub> capture from carbonization in nepheline process***

The main reactions of CO<sub>2</sub> capture by during the carbonization sub-process are:

**Stage 1****Stage 2**

Part of CO<sub>2</sub> after Sintering is passed through gas treatment facilities to remove particles and other harmful components and then forwarded to carbonizers, where the carbonization reaction proceeds step by step. This is done in a two-stage process.

***CO<sub>2</sub> 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<sub>2</sub> and other acid gases it should be assumed that the scrubbing system will remove also some CO<sub>2</sub> in the flue gas. The efficiency of CO<sub>2</sub> 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<sub>2</sub>/CO in flue gas where such scrubbing system is used, it is not recommended that CO<sub>2</sub> removal be considered in CO<sub>2</sub> calculations.

***CO<sub>2</sub> 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<sub>2</sub> and in turn, the capacity of CO<sub>2</sub> to neutralize the highly alkaline red mud. The absorption of CO<sub>2</sub> is rapid and can be efficient if there is good contact between the residue and the CO<sub>2</sub>. For high concentration CO<sub>2</sub> streams (90% or more) the reaction can be virtually 100% with a few seconds contact. Total alkalinity of red mud drops drastically with the added CO<sub>2</sub> recorded as an increase in bicarbonate alkalinity.

For lower concentrations of CO<sub>2</sub> such as flue gas where concentrations may be 12-15%, the reaction efficiency will be reduced. If CO<sub>2</sub> removal data is not available for bauxite residue contacted with gases containing less than 50% CO<sub>2</sub>, then it is recommended that reaction efficiency of 35% be assumed by default.

CO<sub>2</sub> absorption can be estimated by multiplying the quantity of CO<sub>2</sub> 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<sub>2</sub> actually absorbed in the neutralization process.

As mentioned in “CO<sub>2</sub> and methane emissions from organic carbon in bauxite”, when residue is neutralized using CO<sub>2</sub>, the biological activity in the residue deposit and in the collected leachate increases dramatically and can produce CO<sub>2</sub> or CH<sub>4</sub>. Such emissions can be calculated from the carbon reduction levels seen in the residue and leachate, measured in simulations in laboratory environments that duplicate the residue deposit environment, or from direct measurements at the residue site.

## 4.4.5.2 CHOICE OF METHOD

The decision tree in Figure 4.12b 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.

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.

Note that a Tier 2 method is not provided here since country specific emission factors should be gathered at a facility specific level, which means the Tier 3 method.

Should CO<sub>2</sub> capture technology be installed and used at a plant, it is *good practice* to deduct the CO<sub>2</sub> captured in a higher tier emissions calculation. The default assumption is that there is no CO<sub>2</sub> capture and storage (CCS) taking place. Any methodology taking into account CO<sub>2</sub> capture should consider that CO<sub>2</sub> 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<sub>2</sub> are not double counted. In these cases, the total amount of CO<sub>2</sub> captured should preferably be reported in the corresponding energy combustion and IPPU source categories in proportion to the amounts of CO<sub>2</sub> generated in these source categories. For additional information on CO<sub>2</sub> 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

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, BPP and NP alumina production processes) is based on site specific data related to amount of carbonates used in the process. If the Bayer-sinter 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<sub>2</sub>O<sub>3</sub> in ore leads to use of high carbonate content which results in greater GHG emissions. In case of Nepheline processing, GHG emissions from the sintering are depended on the Al<sub>2</sub>O<sub>3</sub> 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, or if a rigorous Tier 3 approach is otherwise deemed impractical, it is *good practice* to use aggregated plant or 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 4.27e:

**EQUATION 4.27E (NEW)**

**TIER 1: SINTERING PROCESS EMISSIONS BASED ON ALUMINA PRODUCTION DATA**

$$CO_2 \text{ Emissions} = M_{Al_2O_3} \cdot S_{Al_2O_3} \cdot EF_{SintAl_2O_3} + M_{Lime} \cdot EF_{Lime}$$

Where:

$CO_2 \text{ Emissions}$  = emissions of CO<sub>2</sub> from sintering production, tonnes

$M_{Al_2O_3}$  = mass of alumina produced, tonnes

$S_{Al_2O_3}$  = mass fraction of alumina produced by sintering process. The parameter can be varied from 0 to 1, where 1 is related to 100% of alumina produced by sintering process.



## Second-order Draft

$EF_{SintAl_2O_3}$  = emission factor for sintering, tonnes CO<sub>2</sub>/tonne alumina (see discussion under Section 4.4.6.3 Choice of Emission Factors), which is not corrected for dust.

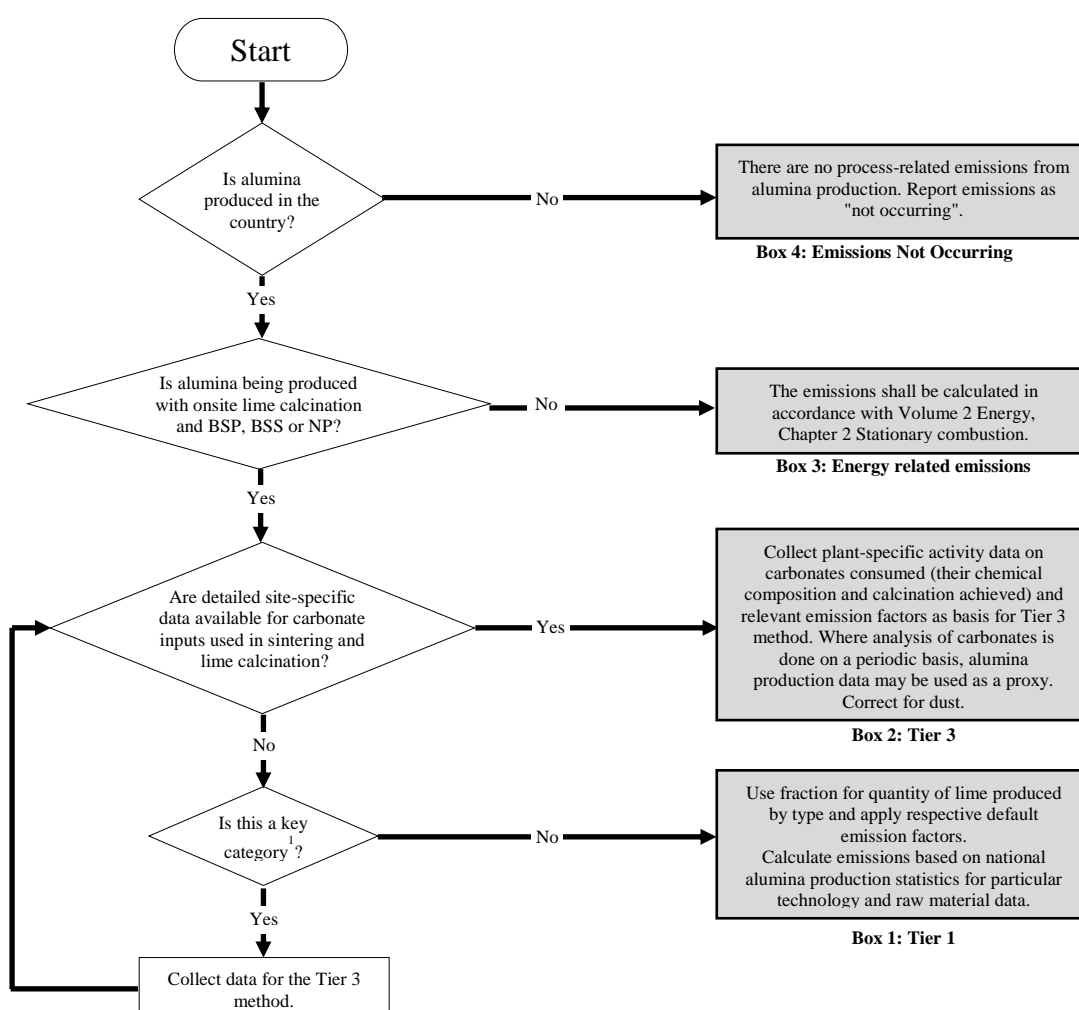
$M_{Lime}$  = mass of lime produced, tonnes.

$EF_{Lime}$  = default emission factor for lime production (Volume 3, Section 2.3.1.2)

The Tier 1 approach is based on the following assumptions about the alumina production and sintering process:

- (iii) The mass fraction of alumina produced by sintering process (rather than the leaching process) is stable over time;
- (iv) In case of alumina production from the nepheline ore, 100% of alumina is produced with the sintering process;
- (v) Plants are generally able to control the CaCO<sub>3</sub> content of the raw material inputs and output of sintering process within close tolerances;
- (vi) The CaCO<sub>3</sub> content of the raw materials inputs from a given plant tends not to change significantly over time;
- (vii) The main source of the CaO for most plants is CaCO<sub>3</sub> 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);
- (viii) 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
- (ix) Dust collectors at plants capture essentially all of the dust.

**Figure 4.12b(new) Decision tree for estimation of CO<sub>2</sub> 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 3: USE OF CARBONATES 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<sub>2</sub> 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 4.27f. 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<sub>2</sub> 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% 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 4.27F (NEW)****TIER 3: EMISSIONS BASED ON CARBONATE RAW MATERIAL INPUTS TO THE SINTERING KILN**

$$CO_2 \text{ Emissions} = \sum_i (M_{oi} \cdot C_{iCO_2}) + E_{LC} + EF_s \cdot M_s + (0.71 C_{Na_2O} \cdot V_s) / 1000 - E_{sp} - E_{rm} - E_{SKD} - E_{nf} \cdot E_{cc}$$

Where:

$CO_2 \text{ Emissions}$  = total emissions of CO<sub>2</sub> from sintering kiln, tonnes

$\sum_i (M_{oi} \cdot C_{iCO_2})$  = CO<sub>2</sub> 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

$C_{iCO_2}$  = the weighted average content of CO<sub>2</sub> in *i* bauxites (nephelines) according to chemical analysis and assumption that 100% calcination will be achieved (in the absence of chemical analysis results, the content of CO<sub>2</sub> in nephelines is determined as the difference in loss on ignition and SO<sub>3</sub>), as given by Equation 4.27I), fraction

$E_{LC}$  = CO<sub>2</sub> emissions released from lime calcination, tonnes CO<sub>2</sub>. 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<sub>2</sub> 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.

$EF_s \cdot M_s$  = CO<sub>2</sub> 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,

## Second-order Draft

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<sub>2</sub> / tonnes soda carbonate (see Table 2.1 Chapter 2 Mineral Industry emissions)

$M_s$  = mass of soda forwarded to the kiln with ore, tonnes

$(0.71 C_{Na_2O} \bullet V_s) / 1000$  = CO<sub>2</sub> emissions from the decomposition of soda contained in a soda solution, tonnes

0.71 = stoichiometric conversion factor of CO<sub>2</sub> from Na<sub>2</sub>O. Na<sub>2</sub>O is measure in the soda solution.

$C_{Na_2O}$  = concentration of sodium oxide (carbonate) in the soda solution, forwarded to the kiln, g/L

$V_s$  = volume of soda solution, m<sup>3</sup>

$E_{sp}$  = CO<sub>2</sub> emissions captured during carbonization process and contained in produced sodium carbonate, tonnes CO<sub>2</sub> (as given by Equation 4.27g)

$E_{rm}$  = CO<sub>2</sub> emissions based on the mass of carbon in bauxite or nepheline residue, tonnes (refer to Equation 4.27j)

$E_{SKD}$  = CO<sub>2</sub> emissions from un-calcined SKD not recycled to the kiln, tonnes (refer to Equation 4.27h)

$E_{nf}$  = CO<sub>2</sub> emissions from carbon-bearing non-fuel materials (as given by Equation 4.27k), tonnes.

$E_{cc}$  = CO<sub>2</sub> absorption through use of circulating water collected from bauxite/nepheline storage residue area and/or absorption through bauxite residue neutralization (as given by Equation 4.27l), tonnes

**EQUATION 4.27G (NEW)****EMISSIONS CAPTURED DURING CARBONIZATION PROCESS AND CONTAINED IN PRODUCED SODIUM CARBONATE**

$$E_{sp} = EF_s \bullet M_{sout}$$

Where:

$E_{sp}$  = CO<sub>2</sub> emissions captured during carbonization process and contained in produced sodium carbonate, tonnes

$EF_s$  = emission factor for soda carbonate forwarded to the kiln with ore tonnes CO<sub>2</sub> / 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 4.27H (NEW)****EMISSIONS FROM UN-CALCINED SKD NOT RECYCLED TO THE KILN**

$$E_{SKD} = ((M_{dr} + M_{dnr}) \bullet E_{ac} / 100 \% - M_{dr}) \bullet C_{CO_2}$$

**OR**

$$E_{SKD} = (M_d \bullet E_{ac} / 100 \% - M_{dr}) \bullet C_{CO_2}$$

Where:

$E_{SKD}$  = CO<sub>2</sub> 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.

$C_{CO_2}$  = carbon content in dust recalculated in CO<sub>2</sub>, fraction.

**EQUATION 4.27I (NEW)**  
**WEIGHTED AVERAGE CONTENT CO<sub>2</sub> IN 'I' BAUXITES (NEPHELINES)**  

$$C_{iCO_2} = \sum_i (EF_i \cdot M_i \cdot F_i)$$

Where:

$C_{CO_2}$  = the weighted average content of CO<sub>2</sub> in  $i$  bauxites (nephelines) according to chemical analysis, assuming 100% calcination of the carbonate, fraction

$EF_i$  = emission factor for the particular carbonate  $i$ , tonnes CO<sub>2</sub> / tonnes carbonate (see Table 2.1 Chapter 2 Mineral Industry emissions)

$M_i$  = mass fraction of carbonate  $i$  consumed in the kiln, fraction

$F_i$  = fraction calcination achieved for carbonate  $i$ , fraction<sup>1</sup>

**EQUATION 4.27J (NEW)**  
**EMISSIONS FROM BAUXITES (NEPHELINES) RESIDUE**  

$$E_{rm} = 44/12 \cdot M_{br} \cdot C_c$$

Where:

$E_{rm}$  = CO<sub>2</sub> emissions based on the mass of carbon in bauxite or nepheline residue, 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 4.27K (NEW)**  
**EMISSIONS FROM CARBON-BEARING NON-FUEL MATERIALS**  

$$E_{nf} = \sum_k (M_k \cdot X_k \cdot EF_k)$$

Where<sup>2</sup>:

$E_{nf}$  = CO<sub>2</sub> 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<sub>2</sub>/tonne carbonate

**EQUATION 4.27L (NEW)**  
**CO<sub>2</sub> ABSORPTION THROUGH USE OF CIRCULATING WATER COLLECTED FROM  
 BAUXITE/NEPHELINE STORAGE RESIDUE AREA AND/OR ABSORPTION THROUGH BAUXITE  
 RESIDUE NEUTRALIZATION**  

$$E_{nf} = V_{gas} \cdot C_{CO_2} \cdot D_{CO_2} \cdot GTE_{CO_2} / 100$$

Where:

<sup>1</sup> For  $F_i$ , calcination fraction (Equation 4.27I): In the absence of actual data, it may be assumed that, at the temperatures and residence times achieved in sintering kilns, the degree of calcination achieved for all material incorporated in the sintering feed is 100 percent (i.e.,  $F_i = 1.00$ ) or very close to it. For SKD, a  $F_i$  of <1.00 is more likely but the data may show high variability and relatively low reliability. In the absence of reliable data for SKD, an assumption of  $F_i = 1.00$  will result in the correction for SKD to equal zero.

<sup>2</sup> The ignored CO<sub>2</sub> emissions from non-carbonate carbon (e.g., carbon in kerogen, carbon in fly ash) in the non-fuel raw materials can be set to zero ( $M_k \cdot X_k \cdot EF_k = 0$ ) if the heat contribution from kerogen or other carbon is < 5% of total heat (from fuels).

## Second-order Draft

$E_{nf}$  = CO<sub>2</sub> absorption through use of circulating water collected from bauxite/nepheline storage residue area and/or absorption through bauxite residue neutralization, tonnes

$V_{gas}$  = exhaust gas volume forwarded to exhaust gas treatment facility, cubic meters

$C_{CO_2}$  = CO<sub>2</sub> concentration in exhaust gas (instrumental measures), fraction of volume

$D_{CO_2}$  = CO<sub>2</sub> destiny under normal conditions, tonn/cubic meters

$GTE_{CO_2}$  = exhaust gas treatment facility efficiency (instrumental measures), percentage

#### 4.4.5.3 CHOICE OF EMISSION FACTORS FOR ALUMINA PRODUCTION

Emission factors for alumina production are as follows. Note that emissions factors for lime production are provided in Volume 3, Section 3.3.1.2.

#### TIER 1 METHOD FOR SINTERING

It is very difficult to define universal default emissions factors because there are no national or industry average data related to bauxite processing by alternative sintering processes. The implementation of these alternative sintering processes is determined by bauxite quality (alumina content), carbonates and silica content in the ore which can vary significantly. However, based on existing data from operating plants it was possible to calculate Tier 1 emissions factors for Bayer-sintering processes and the nepheline-sintering process (NP), for use in Equation 4.27E. For Bayer-sintering process Tier 1 emissions factors can be applied for both parallel (BPP) and sequential (BSS) processes.

TABLE 4.17A (NEW) TECHNOLOGY SPECIFIC DEFAULT EMISSION FACTORS FOR THE CALCULATION OF CO <sub>2</sub> EMISSIONS FROM ALTERNATIVE SINTERING PROCESSES (TIER 1 METHOD)		
Technology	EF <sub>SintAl<sub>2</sub>O<sub>3</sub></sub> (tonne CO <sub>2</sub> /tonne Al)	Uncertainty Range (%) <sup>a</sup>
Bayer-sintering (BSP and BSS)	0.81	-40/+40
Nepheline-sintering process (NP)	2.44	-10/+10
<sup>a</sup> Uncertainty Range is based on expert opinion – analysis of data from known plants and assumption for the plants where CO <sub>2</sub> emissions are unknown.		

Note that a Tier 2 method (and hence Tier 2 emission factors) is not provided here since country specific emission factors should be gathered at a facility specific level, which means the Tier 3 method.

#### TIER 3 METHOD FOR SINTERING

The Tier 3 emission factors are based on the actual CO<sub>2</sub> content of the carbonates present (see Equation 4.27B 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<sub>2</sub> emissions captured by other CO<sub>2</sub> capturing technologies can be calculated using site specific data only. Where such data is unavailable, emissions can be regarded as negligible.

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<sub>2</sub> in bauxite residue 0.1-2% of dry content,
- CO<sub>2</sub> in nepheline residue 0-2% of dry content.

#### 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 (after capture) it may be disposed of. The degree to which SKD can be recycled to the kiln depends on various consideration and usually 100% 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 by 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 burning of liquid or solid fuels. In that case where combustion and process emissions are to be reported separately, e.g. for alumina production, inventory compilers should ensure that the carbon in dust related to fuel combustion are not double counted. In these cases, the total amount of C in dust from fuel burning should preferably be extracted from IPPU source categories in proportion to the amounts of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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, % of alumina produced with sintering. Emissions factors are dependent on bauxite type. For sintering, it is a reasonable assumption that emissions factors for a particular plant, using the same mine, will remain valid for the length of supply; this is because bauxite quality deviations within a mine site are not considered to be so significant as to have an impact on the emissions factor. If the plant has shifted to another source of bauxite, requiring sintering, or if the plant had significant change in technology of sintering, a new emissions factor should be used. Plant specific volume of alumina production, % 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 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 uncalcined 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% 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<sub>3</sub>, but this assumption should be transparently documented.

Activity data should exclude any carbonates that are not fed into the kiln.

#### 1931 **4.4.5.5 COMPLETENESS**

1932 Alumina production data may be available in national statistical databases, or could be collected, if such data have  
1933 not been published in national statistics.

1934 Completeness is a particularly important issue to consider where plant specific data are used to estimate national  
1935 emissions using Tier 3. Under Tier 3, it is important that all alumina plants with lime production and sintering  
1936 processes are considered, and that all carbonates consumed in the sintering process are included in the emission  
1937 calculation. Plants with bauxites/nephelines sintering processes are well identified in each country, but data on the  
1938 fraction weight of carbonates consumed may not be readily available. In order for the Tier 3 method to be  
1939 considered ‘complete’, all carbonates consumed must be recorded.

1940 In countries where only a subset of plants with lime production and bauxites/nephelines sintering processes report  
1941 data for the Tier 3 method, it may not be possible to report emissions using a Tier 3 for all facilities during the  
1942 transition. Where data on the carbonate inputs are not available for all plants to report using Tier 3, it may be  
1943 possible to determine the share of production represented by non-reporting plants and use this information to  
1944 estimate the remaining emissions using Tier 1 in order to ensure completeness during the transition period.

1945 The potential for double counting also should be considered. For example, it is good practice for inventory  
1946 compilers to review statistics used to estimate emissions from the source category ‘Other Process Uses of  
1947 Carbonates’ and ‘Lime production’ to ensure that emissions reported in that source category do not result from the  
1948 use of these carbonates in alumina production. Where carbonates are used for alumina production, it is *good*  
1949 *practice* to report the emissions under Alumina Production. Finally, inventory compilers should include only  
1950 process-related emissions from alumina production in this source category. To avoid double-counting, it is *good*  
1951 *practice* to account for combustion-related emissions in the Energy volume.

1952 There is one additional issue that, while not included in the current methodology, may become relevant for  
1953 consideration in the future. Sodium alkaline contained in bauxite/nepheline residue area can re-absorb atmospheric  
1954 CO<sub>2</sub>. However, the rate of carbonation is very slow (years to centuries).

#### 1955 **4.4.5.6 DEVELOPING A CONSISTENT TIME SERIES**

1956 For lime production, refer to Section 2.3.1.5 in Chapter 2.

1957 Ideally countries shall try to find site specific data for all inventory years. However, often it can be difficult to  
1958 collate historic data for closures, closed operations or if significant changes in changes in technology or sourcing  
1959 of bauxites/nephelines has taken place. In such cases, inventory compilers can consult industry experts to assist  
1960 with extrapolation of CO<sub>2</sub> emission figures (e.g. normalization by volume of alumina production, or based on  
1961 applying of data from similar plants in the reporting country or average worldwide figures for similar technology).

1962 Where data are not available, inventory compilers moving from a Tier 1 to Tier 3 approach may assume that there  
1963 has not been a significant shift in the country from use of one carbonate input to another for Sintering. This is a  
1964 reasonable assumption, specifically since limestone typically is the predominant carbonate input.

### 1965 **4.4.6 Uncertainty assessment for alumina production**

1966 Uncertainty estimates for lime production is described at Section 2.3.2 Uncertainty assessment in Volume 3,  
1967 Chapter 2.

1968 Uncertainty estimates for bauxite/nepheline sintering processes result predominantly from uncertainties associated  
1969 with activity data, and to a lesser extent, from uncertainty related to the emission factor.

#### 1970 **4.4.6.1 EMISSION FACTOR UNCERTAINTIES**

1971 For Tier 1, the major uncertainty component is the emission factor for sintering produced.

1972 For Tier 3, there is relatively little uncertainty associated with the emission factors of the source carbonates because  
1973 they are based on stoichiometric ratios and mass balance.

#### 1974 **4.4.6.2 ACTIVITY DATA UNCERTAINTIES**

1975 The uncertainty for percentage of bauxite/nepheline processing at sintering process is moderate. The level of  
1976 uncertainty is indicated in the Table. 4.17B. The uncertainty in data on alumina production tonnages is about 1  
1977 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%) 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 4.27E-4.27L. 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.



Second-order Draft

<b>TABLE 4.17B (NEW)</b> <b>DEFAULT UNCERTAINTY VALUES FOR BAUXITE/NEPHELINE SINTERING PROCESS</b>		
<b>Uncertainty<sup>a</sup></b>	<b>Comment</b>	<b>Tier</b>
<b>Chemical Analysis / Composition</b>		
1-3%	Percentage of bauxite processing at sintering process	1
10%	Estimation of percentage of bauxite processing at sintering process	1
10%	Emission factor for sintering (NP)	1
40%	Emission factor for sintering (BSP and BSS)	1
10-20%	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%	CO <sub>2</sub> concentration in exhaust gas	3
5%	Exhaust gas treatment facility efficiency	3
1%	CO <sub>2</sub> destiny under normal conditions	3
<b>Production Data</b>		
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 <sub>2</sub> emissions captured by other CO <sub>2</sub> capturing technologies	3
15%	Estimation of CO <sub>2</sub> emissions captured by other CO <sub>2</sub> 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

1993

1994

TABLE 4.17B (NEW) (CONT.) DEFAULT UNCERTAINTY VALUES FOR BAUXITE/NEPHELINE SINTERING PROCESS		
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 <sub>2</sub>	3
10%	Estimation of carbon content in dust recalculated in CO <sub>2</sub>	3
<sup>a</sup> Uncertainty estimates are based on expert judgement.		

1995

## 1996 4.4.7 Quality Assurance/Quality Control (QA/QC), 1997 Reporting and Documentation for alumina 1998 production

### 1999 4.4.7.1 QUALITY ASSURANCE / QUALITY CONTROL (QA/QC)

2000 In addition to the general guidance on QA/QC, specific procedures of relevance to this source category are outlined  
2001 below.

2002

## 2003 COMPARISON OF EMISSIONS ESTIMATES USING DIFFERENT 2004 APPROACHES

2005 Comparisons could be made between estimated emissions using different tiers. For example, if a bottom-up  
2006 approach is used to collect activity data (i.e., collection of plant-specific data), then inventory compilers should  
2007 compare the emissions estimates to the estimates calculated using national production data alumina production  
2008 (top-down approach). In cases where a hybrid Tier 1 or Tier 3 approach is used during a transition period, it is  
2009 considered *good practice* also to estimate emissions for all facilities using the lower Tier in order to compare the  
2010 results of the analysis to the results derived using the hybrid approach. The results of such comparisons should be  
2011 recorded for internal documentation, including explanations for any discrepancies.

2012

## 2013 REVIEW OF EMISSION FACTORS

2014 Inventory compilers should compare aggregated national emission factors with the IPCC default factors in order  
2015 to determine if the national factor is reasonable relative to the IPCC default. Differences between national factors  
2016 and default factors should be explained and documented, particularly if they are representative of different  
2017 circumstances.

2018 If the aggregated top-down approach is used, but some limited plant-specific data are available, inventory  
2019 compilers should compare the site or plant level factors with the aggregated factor used for the national estimate.  
2020 This will provide an indication of the reasonableness and the representability of the data.

2021

**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 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<sub>2</sub> 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.

2059 **4.5 MAGNESIUM PRODUCTION**

2060 No Refinement

2061

2062

Second-order Draft

2063 **4.6 LEAD PRODUCTION**

2064 No Refinement

2065

2066

2067 **4.7 ZINC PRODUCTION**

2068 No Refinement

2069

2070

## 4.8 RARE EARTHS PRODUCTION

[This section provides entirely *new guidance* on the accounting of greenhouse gas emissions (GHG) from the primary production of rare earth (RE) metals and alloys<sup>1</sup>, as part of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (*2019 Refinement*). Since the previous 2006 IPCC Guidelines for National Greenhouse Gas Inventories (*2006 IPCC Guidelines*) has no guidance on the rare earths industry, this is an entirely new sub-chapter 4.8 added to Volume 3, Chapter 4 of the *2006 IPCC Guidelines* (follows on from sub-chapter 4.7 in 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 rare earth (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<sup>2</sup> (refer to sub-chapter 4.4). According to (Vogel & Friedrich 2015; Vogel & Friedrich 2018; Zhang *et al.* 2018), this process consists of:

- Dissolving and electrolytically reducing REOs (e.g. Nd<sub>2</sub>O<sub>3</sub>) in a molten salt of rare earth fluorides (REF<sub>3</sub>) and lithium fluoride (LiF) – an example composition is 85% wt NdF<sub>3</sub>, 10% LiF and 5% Nd<sub>2</sub>O<sub>3</sub> for Nd metal production;
- Carbon anodes (e.g. graphite), that are consumed in the process;
- Cathodes, that 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) and depending on the technology, may be periodically interrupted or disturbed by anode replacements, cathode removal/replacement and removal of liquid RE metal/alloy, etc.

Neodymium (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 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

<sup>1</sup> Carbon dioxide (CO<sub>2</sub>) emissions associated with the production of electricity from fossil fuel combustion to produce rare earth metals and alloys are covered in Volume 2: Energy.

<sup>2</sup> 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<sub>2</sub> 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, direct comparisons between the two processes are not entirely valid.

automatic process control features, including automatic feeding of REOs and automatic detection of anode effects that generate perfluorocarbon GHGs (refer to section 4.8.2.2).

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. Carbon dioxide (CO<sub>2</sub>) emissions from the consumption of carbon anodes in the electrolytic reaction converting rare earth oxides to rare earth metals;
2. Perfluorocarbons (PFCs) emissions of CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub> during anode effects. While not commonly observed, very low levels of C<sub>3</sub>F<sub>8</sub> and trace levels of other PFCs (e.g. c-C<sub>4</sub>F<sub>8</sub> and C<sub>4</sub>F<sub>10</sub>) have also been reported (Cai *et al.* 2018).

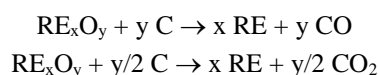
Carbon monoxide (CO) is another major process emission; SO<sub>2</sub> might also be emitted in very small amounts.

The decision trees in Figure 4.17 and Figure 4.18 provide guidance for selecting a methodology estimating CO<sub>2</sub> and PFC emissions, respectively, from rare earth metal production. Where 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.

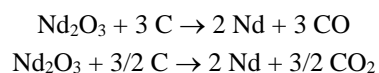
## 4.8.2 Methodological Issues

### 4.8.2.1 CHOICE OF METHOD FOR CO<sub>2</sub> EMISSIONS FROM PRIMARY RARE EARTH METAL PRODUCTION

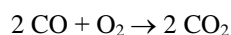
During normal operations, rare earth metals are produced at the cathode and carbon is consumed at the anode, forming carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) gases by electrolysis, as per the generic electrolytic reduction reactions below for production of any rare earth metal (RE) from its oxide (REO) (Liu *et al.* 2001; Vogel *et al.* 2017) :



An example reaction for Nd metal production from its oxide is as follows:



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<sub>2</sub> gas (Vogel & Friedrich 2018), as follows:



Most CO<sub>2</sub> emissions therefore result from the electrolysis reaction of the carbon anode with rare earth oxides (REO). The consumption of carbon anodes<sup>1</sup> is the principal source of process related CO<sub>2</sub> emissions from primary rare earth production. The reactions leading to CO<sub>2</sub> 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, all other sources of process-related CO<sub>2</sub> emissions have not been considered in these guidelines. For example, it is assumed that industrial rare earth facilities currently do not

<sup>1</sup> It is assumed that all rare earth smelting facilities employing the fluoride-salt electrolysis process uses carbon anodes that have been prebaked by external facilities. As such, GHGs from the anode baking process and any associated energy use should be accounted for outside of the rare earth industry.

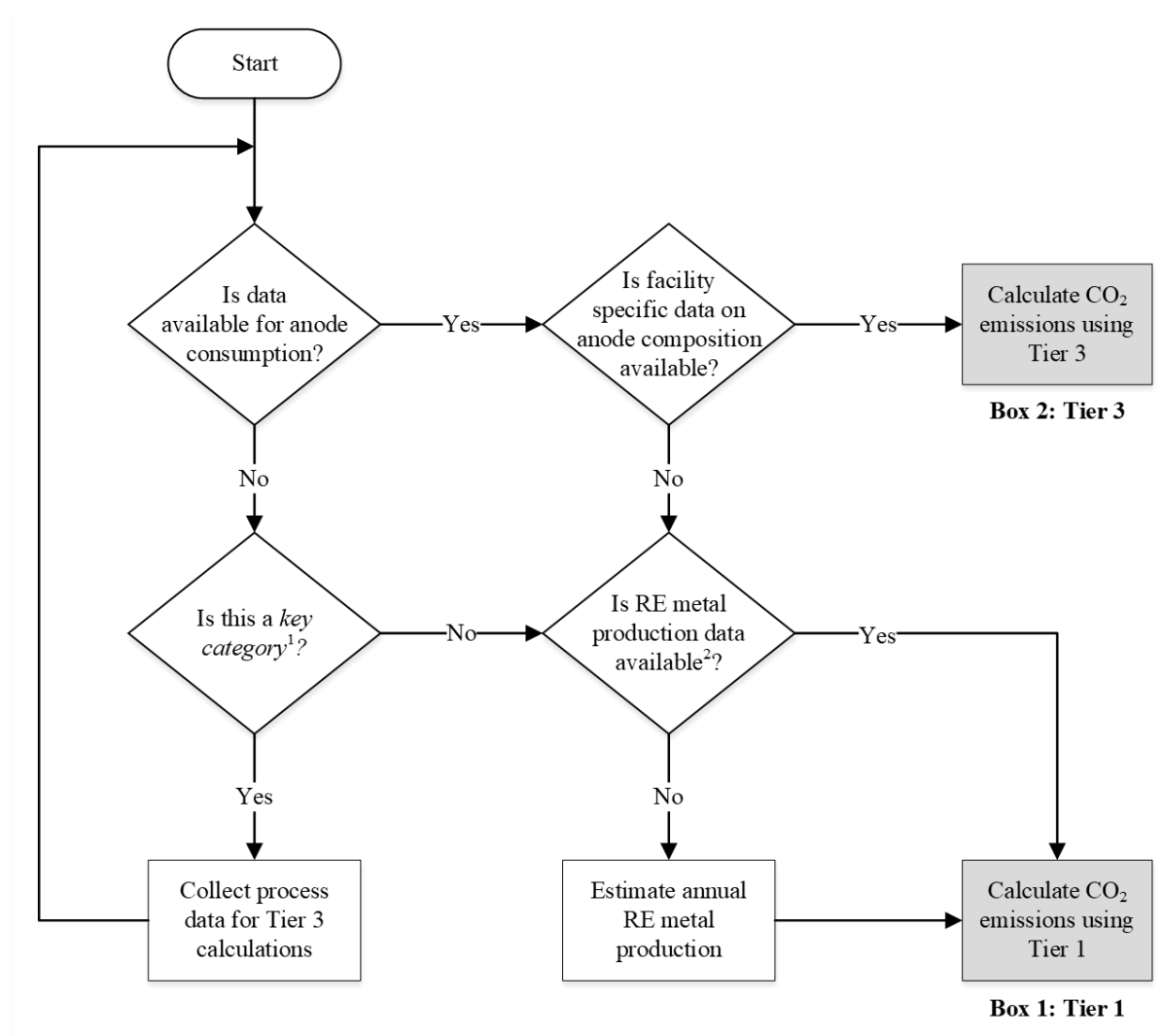


## Second-order Draft

manufacture or ‘pre-bake’ their own carbon anodes (due to low process volumes compared to the primary aluminium industry, refer to sub-chapter 4.4.2.1) and hence GHGs from anode baking are not considered here.

The decision tree shown in Figure 4.17 describes good practice in choosing the CO<sub>2</sub> inventory methodology appropriate for national circumstances.

**Figure 4.17 (new) Decision tree for calculation of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions – default emission factors

The Tier 1 method for calculating CO<sub>2</sub> emissions uses a lower order estimate based only on rare earth metal production. Given the uncertainty associated with the Tier 1 method, it is *good practice* to use higher tier methods if CO<sub>2</sub> from primary rare earths is a key category.

Total CO<sub>2</sub> emissions from all rare earth (RE) metals and alloys produced are calculated according to Equation 4.35.

**EQUATION 4.35 (NEW)**  
**PROCESS CO<sub>2</sub> EMISSIONS FROM ANODE CONSUMPTION (TIER 1)**

$$E_{CO_2} = \sum_i (EF_i \cdot MP_i)$$

Where:

$E_{CO_2}$  = Total CO<sub>2</sub> emissions from carbon anode consumption (tonnes CO<sub>2</sub>)

$EF_i$  = Specific emission factor for RE metal/alloy type  $i$  (tonnes CO<sub>2</sub>/tonne RE metal)

$MP_i$  = Total metal production for RE metal/alloy type  $i$  (tonnes RE metal)

Note that while Equation 4.35 enables calculation of CO<sub>2</sub> emissions by each RE metal/alloy produced (assuming production data for each metal and alloy type  $i$  is available), the scarcity of published data means that individual default emission factors are not available for individual RE metals and alloys<sup>1</sup>. Only one default Tier 1 emission factor for a generic RE metal has been provided in these guidelines (refer to Table 4.26). Therefore, it is acceptable to use Equation 4.35 with total RE metal production data, without differentiation into RE metal and alloy types.

### **Tier 3 method for CO<sub>2</sub> emissions – by facility-specific carbon mass balance**

In the Tier 3 method, CO<sub>2</sub> emissions are calculated using a mass balance approach that assumes that the carbon content of net anode consumption<sup>2</sup> is all ultimately emitted to the atmosphere as CO<sub>2</sub> gas<sup>3</sup>. The Tier 3 method uses actual concentrations of anode impurities from each facility; default impurity values are not provided in these guidelines due to a lack of published data. 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 is not available due to the scarcity of published information.

CO<sub>2</sub> 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).

**EQUATION 4.36 (NEW)**  
**PROCESS CO<sub>2</sub> EMISSIONS FROM ANODE CONSUMPTION (TIER 3)**

$$E_{CO_2} = \sum_i (NAC_i \cdot MP_i) \cdot [(100 - Imp_a) / 100] \cdot (44 / 12)$$

Where:

$E_{CO_2}$  = Total CO<sub>2</sub> emissions from carbon anode consumption (tonnes CO<sub>2</sub>)

$NAC_i$  = Net anode consumption per tonne of RE metal/alloy type  $i$  (tonnes/tonne RE metal)

$MP_i$  = Total metal production for RE metal/alloy type  $i$  (tonnes RE metal)

<sup>1</sup> While Tier 1 default emission factors are not available for individual RE metal/alloy types, Equation 4.35 has been provided as a template for when such factors might become available in the future.

<sup>2</sup> ‘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.

<sup>3</sup> 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<sub>2</sub> gas. The same carbon mass-balance approach is assumed for the primary aluminium industry, in sub-chapter 4.4.2.1.

## Second-order Draft

2216  $Imp_a$  = Total content of non-carbon impurities (e.g. sulfur, ash, etc) in baked carbon anodes (wt %)

2217  $44/12$  = CO<sub>2</sub> molecular mass: carbon atomic mass ratio (dimensionless)

2218

2219 Equation 4.36 can be applied to each rare earth smelter in the country and the results summed to arrive at total  
2220 national emissions.

2221 It is possible to use a hybrid Tier 1 and 3 approach if facility specific net anode consumption and composition data  
2222 (impurity content, e.g. ash, sulfur, etc) are not available for each smelter.

2223

## 2224 4.8.2.2 CHOICE OF EMISSION FACTORS FOR CO<sub>2</sub> EMISSIONS FROM 2225 PRIMARY RARE EARTH METAL PRODUCTION

### 2226 Tier 1 method for CO<sub>2</sub> emissions

2227 Table 4.26 lists the default emission factors for CO<sub>2</sub> per tonne of RE metal, for use in Equation 4.35. Given the  
2228 scarcity of published data and since only minor differences in emission factors are expected across different RE  
2229 metals and alloy types<sup>1</sup>, only one default emission factor is provided for all RE metals. This uses Nd metal  
2230 production as the basis, since it is the most common RE metal produced via fluoride-salt electrolysis.

2231

TABLE 4.26 (NEW) TIER 1 DEFAULT EMISSION FACTORS FOR CALCULATING CO <sub>2</sub> EMISSIONS FROM ANODE CONSUMPTION		
Rare Earth Metal / Alloy <i>i</i>	Emission Factor, $EF_i$ (tonnes CO <sub>2</sub> /tonne RE metal)	Uncertainty Range (±%)
Nd metal, and all other Rare Earth metals/alloys	0.56 <sup>a</sup>	±10% <sup>b</sup>
Source: <sup>a</sup> CO <sub>2</sub> 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 <i>et al.</i> 2018)) and converting this to CO <sub>2</sub> by mass balance, assuming 100% conversion of anode carbon to CO <sub>2</sub> . <sup>b</sup> Uncertainty range lower and upper bounds for the default CO <sub>2</sub> emission factor is based on respective lowest and highest CO <sub>2</sub> emissions estimated from industrial net carbon anode consumption values and converted by mass balance to CO <sub>2</sub> (Cai <i>et al.</i> 2018). However, unpublished data from direct measurement of CO <sub>2</sub> from industrial rare earth facilities suggests the uncertainty range could be in the range of -70%/+20% from the default factor (expert opinion). Furthermore, assuming the default factor represents a current efficiency of 75%, an uncertainty range of -22%/+24% from the default CO <sub>2</sub> 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 the footnote <sup>1</sup> . Therefore where possible, development and use of Tier 3 emission factors is encouraged.		

2232

### 2233 Tier 3 method for CO<sub>2</sub> emissions

2234 Table 4.27 lists the facility-specific activity data (and uncertainties) at individual facilities, for use in Equation  
2235 4.36. The most significant factors in Equation 4.36 are metal production and net anode consumption for each RE  
2236 metal or alloy type *i*. Both these parameters should be collected from individual operating facilities for use with  
2237 Tier 3. The other compositional terms in the equation make minor adjustments for non-carbon components of the  
2238 anodes (e.g. sulphur and ash, expected to be <3% wt) and thus are not as critical. Tier 3 is based on the use of  
2239 specific operating facility data for these minor components. Carbon consumed per tonne of metal produced is

<sup>1</sup> A difference of only -4% / +8% in CO<sub>2</sub> emission factors was estimated across different rare earth metals (from La to Gd metal, using Nd metal as a base case), when evaluating CO<sub>2</sub> emissions by first principles. This is due to the similarities in atomic mass for these rare earth metals. A first principles calculation for CO<sub>2</sub> was done by taking electrolysis of Nd<sub>2</sub>O<sub>3</sub> 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<sub>2</sub> by direct electrolysis at 1050°C and anode current density of 1.0 A/cm<sup>2</sup> (Liu *et al.* 2001); Vogel and Friedrich (2015). CO<sub>2</sub> emitted is then calculated assuming: (i) all CO is ultimately oxidised to CO<sub>2</sub>, (ii) process has a 75% faradaic current efficiency (% anode carbon that is 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 carbon / tonne RE metal) is similar to figures obtained from industrial rare earth surveys (Cai *et al.* 2018).

typically recorded by rare earth production facilities given its economic significance; facilities can refer to this as ‘net anode consumption’ or ‘net carbon consumption’.

<b>TABLE 4.27 (NEW)</b> <b>DATA SOURCES AND UNCERTAINTIES FOR PARAMETERS USED IN TIER 3 METHOD FOR CO<sub>2</sub> EMISSIONS FROM ANODE CONSUMPTION</b>		
<b>Parameter</b>	<b>Data Source</b>	<b>Uncertainty (±%)</b>
<i>MP<sub>i</sub></i> : total metal production for RE metal type <i>i</i> (tonnes metal per year)	Individual facility records	±10% <sup>a</sup>
<i>NAC<sub>i</sub></i> : net anode consumption per tonne of RE metal type <i>i</i> (tonnes per tonne metal)	Individual facility records	±10% <sup>b</sup>
<i>Imp<sub>a</sub></i> : total non-carbon impurity content in baked anodes (wt %) <sup>c</sup>	Individual facility records	±10% <sup>b</sup>
Source: <sup>a</sup> Uncertainties in facility specific metal production records are expected to be low (i.e. ±10%), 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 of rare earth oxides in 2015, due to unreported / illegal production of RE metals (Kingsnorth 2015). <sup>b</sup> Uncertainties for CO <sub>2</sub> 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 <sub>2</sub> emissions from prebake cells). <sup>c</sup> Non-carbon impurities can include sulfur, 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<sub>x</sub>F<sub>y</sub>) and lithium fluoride (LiF). An example melt composition for Nd metal production is 85% wt NdF<sub>3</sub>, 10% LiF and 5% Nd<sub>2</sub>O<sub>3</sub>.

Perfluorocarbons (mainly CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub> – collectively referred to as PFCs) are formed from the reaction of the carbon anode with the fluoride melt (e.g. NdF<sub>3</sub> or DyF<sub>3</sub>) 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<sub>2</sub> 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<sub>4</sub> and C<sub>2</sub>F<sub>6</sub>, other PFCs reported by Cai *et al.* (2018) during RE metal production included: very low levels of C<sub>3</sub>F<sub>8</sub> (<1% total PFCs) and trace levels of c-C<sub>4</sub>F<sub>8</sub> and C<sub>4</sub>F<sub>10</sub> (<0.05% total PFCs). However, quantification of these PFCs (other than CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub>) in industrial measurements is extremely challenging and often impractical, given the extremely low detection limits required.

<b>BOX 4.3 (NEW)</b> <b>ANODE EFFECT DESCRIPTION (FOR RARE EARTH METAL PRODUCTION BY FLUORIDE ELECTROLYSIS)</b>	
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. This often causes voltage to be elevated above normal operating range; however, PFC generation might also occur in the absence of detectable changes in voltage (Vogel <i>et al.</i> 2017; Kjos <i>et al.</i> 2018).  Unlike the analogous primary aluminium industry (refer to Box 4.1A), 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.	

## Second-order Draft

2270 Due to reported differences in emissions profile (Cai *et al.* 2018; Zhang *et al.* 2018), PFC emissions can be  
 2271 estimated separately for two groups of rare earth metals and alloys:

- 2272 • *Rare earth-iron (RE-Fe) alloys*<sup>1</sup> with high melting-point (>1300°C) rare earth elements, e.g. Dy-Fe, Gd-  
 2273 Fe and Ho-Fe;
- 2274 • *All other rare earth (Other-RE) metals/alloys* including single and mixed rare earth metals, e.g. Nd, La,  
 2275 Pr-Nd, etc.

2276 In choosing a method for PFC emissions, it should be noted that the uncertainty associated with the Tier 3  
 2277 methodology is significantly lower than for Tier 1; therefore Tier 3 is strongly recommended if this is a *key*  
 2278 *category*. However, a pre-requisite for the Tier 3 method is the availability of facility-specific emission factors.  
 2279 While no guidance currently exists on how to obtain these for the rare earth industry, the US EPA and IAI protocols  
 2280 for measurement of PFCs in the aluminium smelting industry provide good analogous references (International  
 2281 Aluminium Institute 2006; US Environmental Protection Agency & International Aluminium Institute 2008).

2282 The decision tree in Figure 4.18 describes *good practice* in choosing the PFC inventory methodology appropriate  
 2283 for national circumstances. The Tier 3 approach is preferred because plant-specific emission factors will lead to  
 2284 estimates that are more accurate. If no PFC measurements have been made to establish Tier 3 plant-specific  
 2285 emission factors, the Tier 1 method can be used until measurements have been made. Countries can use a  
 2286 combination of Tier 1 and Tier 3 depending on whether plant-specific emission factors are available from  
 2287 individual facilities.

2288 Note that while the fundamentals mechanisms that generate PFCs and anode effects in the rare earths industry are  
 2289 similar to those in primary aluminium production (refer to sub-chapter 4.4), the lack of automation currently found  
 2290 in the rare earths industry prevents the use of facility-specific activity data (e.g. using anode effect performance  
 2291 data as per Tier 2 and 3 methods for PFC accounting in primary aluminium production) as a more accurate  
 2292 methodology for estimating PFCs. Therefore, higher Tier 2 and 3 methods using process performance statistics or  
 2293 activity data have not been included in these guidelines<sup>2</sup>.

2294

2295

2296

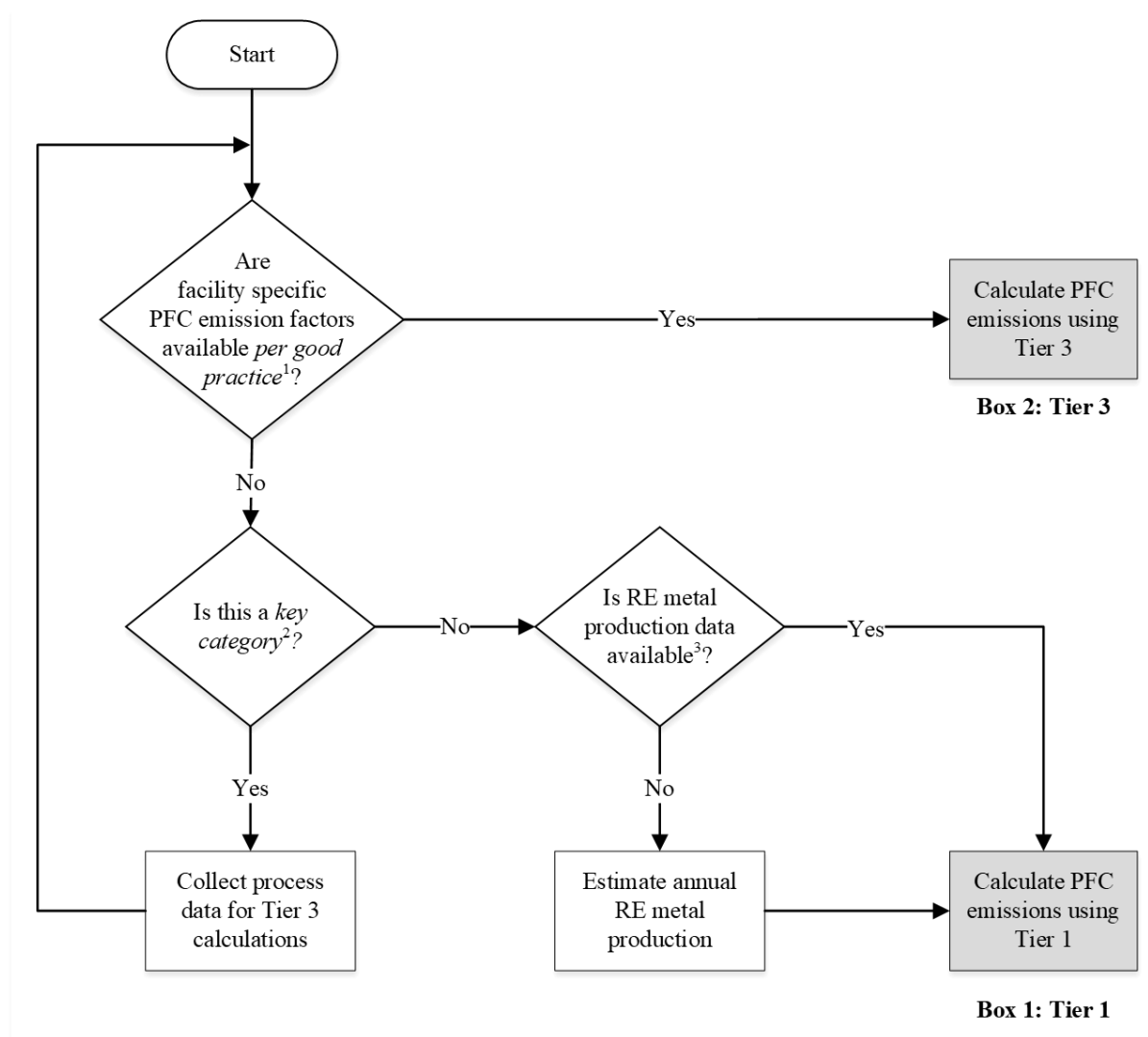
2297

---

<sup>1</sup> 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) and high operating cell voltage (compared to cells for all other RE metals/alloys in similar conditions); the higher operating temperature and cell voltage is thought to be one of the reasons behind higher PFC emissions (Cai *et al.* 2018, Zhang *et al.* 2018).

<sup>2</sup> 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.

**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.

## Second-order Draft

**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<sub>4</sub> and C<sub>2</sub>F<sub>6</sub> gases since these are the major PFCs generated. C<sub>3</sub>F<sub>8</sub> is also included for sake of completeness, however it is a very minor component of PFCs generated in rare earths (<1% 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. PFC emissions can be calculated according to Equation 4.37, where emission factors for CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub> and C<sub>3</sub>F<sub>8</sub> 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<sup>1</sup> are not taken into account.

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<sup>2</sup>. 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 (TIER 1 AND TIER 3)**

$$E_{CF4} = \sum_i [(EF_{CF4, i} / 1000) \cdot MP_i]$$

and

$$E_{C2F6} = \sum_i [(EF_{C2F6, i} / 1000) \cdot MP_i]$$

and

$$E_{C3F8} = \sum_i [(EF_{C3F8, i} / 1000) \cdot MP_i]$$

Where:

$E_{CF4}$  = Emissions of CF<sub>4</sub> from RE metal production, kg CF<sub>4</sub>

$E_{C2F6}$  = Emissions of C<sub>2</sub>F<sub>6</sub> from RE metal production, kg C<sub>2</sub>F<sub>6</sub>

$E_{C3F8}$  = Emissions of C<sub>3</sub>F<sub>8</sub> from RE metal production, kg C<sub>3</sub>F<sub>8</sub>

$EF_{CF4, i}$  = Emission factor by RE metal *i* for CF<sub>4</sub>, g CF<sub>4</sub>/tonne RE metal

$EF_{C2F6, i}$  = Emission factor by RE metal *i* for C<sub>2</sub>F<sub>6</sub>, g C<sub>2</sub>F<sub>6</sub>/tonne RE metal

$EF_{C3F8, i}$  = Emission factor by RE metal *i* for C<sub>3</sub>F<sub>8</sub>, g C<sub>3</sub>F<sub>8</sub>/tonne RE metal

$MP_i$  = Metal production by RE metal *i*, tonnes RE metal

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

<sup>1</sup> 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.

<sup>2</sup> 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.

Environmental Protection Agency & International Aluminium Institute 2008)). It is recommended that Tier 3 be used when PFCs from rare earths is a *key category*, provided facility-specific emission factors are available <sup>1</sup>.

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 is 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<sub>3</sub>F<sub>8</sub>, 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<sub>3</sub>F<sub>8</sub>; Tier 3 emission factors for CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub>).

#### 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. (refer to 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 <sub>4</sub>		C <sub>2</sub> F <sub>6</sub>		C <sub>3</sub> F <sub>8</sub>	
Rare Earth Metal, <i>i</i>	<i>EF</i> <sub>CF<sub>4</sub></sub> (g/tonne RE metal)	Uncertainty Range <sup>c</sup> (+/- %)	<i>EF</i> <sub>C<sub>2</sub>F<sub>6</sub></sub> (g/tonne RE metal)	Uncertainty Range <sup>c</sup> (+/- %)	<i>EF</i> <sub>C<sub>3</sub>F<sub>8</sub></sub> (g/tonne RE metal)	Uncertainty Range <sup>c</sup> (+/- %)
RE-iron alloys (Dy-Fe, etc) <sup>a</sup>	146.1	+/- 99%	14.6	+/- 99%	0.05	+/- 99%
Other-RE metals/alloys (Nd, Pr-Nd, La, etc) <sup>b</sup>	35.8	-54% / +30%	5.2	-95% / +108%	0.21	-52% / +30%
Sources:						
<sup>a</sup> For <i>rare earth-iron (RE-Fe) alloys</i> , CF <sub>4</sub> default emission factors is based on the average of two industrial measurements from production of Dy-Fe alloy (1 cell) in China (Cai <i>et al.</i> 2018; Zhang <i>et al.</i> 2018). C <sub>2</sub> F <sub>6</sub> and C <sub>3</sub> F <sub>8</sub> default emission factors were calculated using the CF <sub>4</sub> default factor, multiplied by the respective C <sub>2</sub> F <sub>6</sub> /CF <sub>4</sub> and C <sub>3</sub> F <sub>8</sub> /CF <sub>4</sub> ratio measured by (Cai <i>et al.</i> 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.						
<sup>b</sup> For <i>all other rare earth (Other-RE) metals/alloys</i> , CF <sub>4</sub> default emission factors is based on the average of industrial measurements from production of: (i) Nd metal (16 cells) (Zhang <i>et al.</i> 2018) and (ii) Pr-Nd alloy (15 cells, 6 cells) and La metal (6 cells) in China (Cai <i>et al.</i> 2018). C <sub>2</sub> F <sub>6</sub> and C <sub>3</sub> F <sub>8</sub> default emission factors were calculated using the CF <sub>4</sub> default factor, multiplied by the average C <sub>2</sub> F <sub>6</sub> /CF <sub>4</sub> and C <sub>3</sub> F <sub>8</sub> /CF <sub>4</sub> ratio, respectively, measured by (Cai <i>et al.</i> 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.						
<sup>c</sup> Note that the default factors and uncertainty ranges here have been estimated with very limited sources of industrial data. However, other 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 <sub>3</sub> inputs to replace consumed fluorides). Therefore where possible, development and use of Tier 3 facility-specific PFC emission factors is encouraged.						

<sup>1</sup> Determination of Tier 3 facility-specific emission factors for C<sub>3</sub>F<sub>8</sub> 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<sub>3</sub>F<sub>8</sub> emissions are estimated using Tier 1 default factors, and CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub> using Tier 3, respectively.



## Second-order Draft

**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 <sub>4</sub> emission factor for metal type $i$ (kg CF <sub>4</sub> /tonne RE metal)	Individual facility records	±10% <sup>a</sup>
$EF_{C2F6}$ : C <sub>2</sub> F <sub>6</sub> emission factor for metal type $i$ (kg C <sub>2</sub> F <sub>6</sub> /tonne RE metal)	Individual facility records	±10% <sup>a</sup>
$EF_{C3F8}$ : C <sub>3</sub> F <sub>8</sub> emission factor for metal type $i$ (kg C <sub>3</sub> F <sub>8</sub> /tonne RE metal)	Individual facility records	±35% <sup>a</sup>
$MP_i$ : metal production for RE metal type $i$ (tonnes metal per year)	Individual facility records	±10% <sup>b</sup>
Source: <sup>a</sup> 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 <i>et al.</i> 2018). Uncertainties for C <sub>2</sub> F <sub>6</sub> and especially C <sub>3</sub> F <sub>8</sub> can be higher, particularly when concentrations are close to detection limits of gas measurement systems. <sup>b</sup> Uncertainties in facility specific metal production records should be low (i.e. ±10%), 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 of rare earth oxides in 2015, due to unreported / illegal production of RE metals (Kingsnorth 2015).		

**4.8.2.5 CHOICE OF ACTIVITY DATA & EMISSION FACTORS**

Production statistics should be available from every facility to enable use of the Tier 1 methods for both CO<sub>2</sub> 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% uncertainty); other sources (Vogel & Friedrich 2018) estimate up to ±40% 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 good measurements have been taken to establish facility-specific emission factors.

For CO<sub>2</sub> 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<sub>2</sub> emissions.

**4.8.2.6 COMPLETENESS**

Primary RE metal production facilities (by fluoride-electrolysis of REOs) should have good 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 should 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) and care should be exercised to avoid omissions of carbon dioxide associated with electricity input (this should be captured separately under Volume 2: Energy), or to avoid double counting of this carbon dioxide.

**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<sub>2</sub> 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<sub>2</sub> emissions is smaller, but still significant.

### 4.8.3.1 EMISSION FACTOR UNCERTAINTIES

#### Uncertainties in CO<sub>2</sub> emission factors

For CO<sub>2</sub> emissions, there are major differences in the uncertainty of emissions depending on the choice of Tier 1 or 3 methods. The uncertainty in emission factors for calculating CO<sub>2</sub> emissions from carbon anode consumption for Tier 3 should be less than  $\pm 20\%$ , and less than  $\pm 25\%$ <sup>1</sup> 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<sub>2</sub>), 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% 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 much lower uncertainty in calculating CO<sub>2</sub> 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<sub>2</sub> 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 extremely 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) and modelled emission estimates of PFCs (Vogel & Friedrich 2018), the range of which span across several orders of magnitude. Furthermore, due to the limited number of industrial measurements and modelled emission factors, 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, there Tier 3 coefficients will have an uncertainty of  $\pm 10\%$  for CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub> and  $\pm 35\%$  for C<sub>3</sub>F<sub>8</sub> at the time coefficients are measured (Cai *et al.* 2018).

---

<sup>1</sup> The overall uncertainty for CO<sub>2</sub> emissions estimation by Tier 1 is less than  $\pm 25\%$ , if the uncertainty range for Tier 1 CO<sub>2</sub> emission factors is taken to be  $-22/+24\%$ , based on the range of possible current efficiency values (60-95%). This is because current efficiency impacts net anode consumption and therefore estimation of CO<sub>2</sub> emissions by mass balance; refer to note 'b' under Table 4.26 for details.

### 4.8.3.2 ACTIVITY DATA UNCERTAINTIES

While uncertainties in annual production data for RE metals should be minor (less than  $\pm 10\%$ ), there are some reports of unreported/illegal production in parts of the world that amount to  $\pm 40\%$  of estimated global metal production in 2015 (Kingsnorth 2015; Vogel & Friedrich 2018). The uncertainty in recorded carbon anode consumption is estimated to be similar (less than  $\pm 10\%$ ).

## 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<sub>2</sub> 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<sub>2</sub> 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<sub>4</sub>) and Hexafluoroethane (C<sub>2</sub>F<sub>6</sub>) 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<sup>1</sup>. Inventory compilers should 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  $\pm 20\%$ <sup>2</sup> 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  $\pm 100\%$ <sup>3</sup>. 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.

<sup>1</sup> 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.

<sup>2</sup> Inter-annual variations in CO<sub>2</sub> emissions in the analogous aluminium industry (sub-chapter 4.4) typically do not vary more than  $\pm 10\%$ ; given the scarcity of published data, greater variations might be allowed for in the rare earth industry.

<sup>3</sup> Inter-annual variations in PFC emissions in the analogous aluminium industry (sub-chapter 4.4) typically do not vary more than  $\pm 100\%$ ; 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<sub>4</sub>, C<sub>2</sub>F<sub>6</sub> and C<sub>3</sub>F<sub>8</sub> 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 <sub>2</sub> AND PFC EMISSIONS FROM RARE EARTH METAL PRODUCTION BY TIER		
Data	Tier 3	Tier 1
<b>CO<sub>2</sub> emissions</b>		
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	
<b>PFC emissions (CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub> and C<sub>3</sub>F<sub>8</sub> reported separately on mass basis)</b>		
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

## References

### SECTION 4.2

- EEA (2005). EMEP/CORINAIR. Emission Inventory Guidebook – 2005, European Environment Agency, Technical report No 30. Copenhagen, Denmark, (December 2005). Available from web site see: [http://reports.eea.eu.int/EMEP\\_CORINAIR4/en](http://reports.eea.eu.int/EMEP_CORINAIR4/en)
- European IPPC Bureau (2001). Integrated Pollution Prevention and Control (IPPC) Best Available Techniques Reference Document on the Production of Iron and Steel, December 2001. <http://eippcb.jrc.es/pages/FActivities.htm>
- International Iron and Steel Institute (2004). Steel Statistical Yearbook 2004: International Iron and Steel Institute, COMMITTEE ON ECONOMIC STUDIES, Brussels.
- Pipatti, R. (2001). Greenhouse Gas Emissions and Removals in Finland, Report No. 2094, VTT Technical Research Centre of Finland, Espoo, 2001. <http://virtual.vtt.fi/inf/pdf/tiedotteet/2001/T2094.pdf>
- Schoenberger, H. (2000). 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.
- EMEP/EEA (2016). Air pollutant emission inventory guidebook 2016, available at <https://www.eea.europa.eu/publications/emep-eea-guidebook-2016>.
- ISO 14404-1:2013 (2013). Calculation method of carbon dioxide emission intensity from iron and steel production – Part 1: Steel plant with blast furnace, available at <https://www.iso.org/standard/57298.html>.
- ISO 14404-2:2013 (2013). Calculation method of carbon dioxide emission intensity from iron and steel production – Part 2: Steel plant with electric arc furnace (EAF), available at <https://www.iso.org/standard/57299.html>.
- IPPC (2001). Integrated Pollution Prevention and Control (IPPC), Best Available Techniques Reference Document on the Production of Iron and Steel, December 2001, available at [http://eippcb.jrc.ec.europa.eu/reference/BREF/isp\\_bref\\_1201.pdf](http://eippcb.jrc.ec.europa.eu/reference/BREF/isp_bref_1201.pdf).
- International Iron and Steel Institute (2004). Steel Production: Consensus of experts and IISI Environmental Performance Indicators 2003 STEEL.
- JRC Reference report (2013). Best Available Techniques (BAT) Reference Document for Iron and Steel Production, 2013, available at [http://eippcb.jrc.ec.europa.eu/reference/BREF/IS\\_Adopted\\_03\\_2012.pdf](http://eippcb.jrc.ec.europa.eu/reference/BREF/IS_Adopted_03_2012.pdf).
- Official Journal of the European Union (2011). Commission Decision of 27 April 2011 determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council, available at <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32011D0278>.
- Official journal of European Union (2011). Average performance of 10% most efficient installation in EU for the year of 2007-2008, “Benchmark value for steel industry under the EU-ETS“ (May 2011).
- Fruehan R.J., Fortini O., Paxton H.W., Brindle R. (2000). Theoretical Minimum Energies To Produce Steel for Selected Conditions, Prepared under contract to Energetics, Inc. Columbia, MD For the U.S. Department of Energy Office of Industrial Technologies Washington., DC Carnegie Mellon University Pittsburgh, PA, March 2000, available at [https://www.energy.gov/sites/prod/files/2013/11/f4/theoretical\\_minimum\\_energies.pdf](https://www.energy.gov/sites/prod/files/2013/11/f4/theoretical_minimum_energies.pdf).
- ThyssenKrupp Industrial Solutions AG, Coke plant technologies, available at [https://www.thyssenkrupp-industrial-solutions.com/media/products\\_services/coke\\_plants/tkis\\_coke\\_plant\\_technologies.pdf](https://www.thyssenkrupp-industrial-solutions.com/media/products_services/coke_plants/tkis_coke_plant_technologies.pdf)
- U.S. Environmental Protection Agency (2012). Available and Emerging Technologies for Reducing Greenhouse Gas, Emissions from the Iron and Steel Industry, Sector Policies and Programs Division, Office of Air Quality Planning and Standards, September 2012, available at <https://www.epa.gov/sites/production/files/2015-12/documents/ironsteel.pdf>.
- U.S. Environmental Protection Agency (2009). Technical support document for the iron and steel sector: proposed rule for mandatory reporting of Greenhouse, Office of Air and Radiation, 2009, available at <https://nepis.epa.gov/Exe/tiff2png.cgi/P1009F3X.PNG?-r+75+-g+7+D%3A%5CZYFILES%5CINDEX%20DATA%5C06THRU10%5CTIFF%5C00001014%5CP1009F3X.TIF> EMEP/EEA.

Zhang X., Wu G.,WU S., Xiang X. (2011). Determination of carbon dioxide emission factors in typical processes for large iron-steel companies, available at: [http://www.actasc.cn/hjxxb/ch/reader/create\\_pdf.aspx?file\\_no=20111012001](http://www.actasc.cn/hjxxb/ch/reader/create_pdf.aspx?file_no=20111012001).

#### SECTION 4.4

Asheim, H., Aarhaug, T. A., Ferber, A., Kjos, O. S. & Haarberg, G. M. (2014) Monitoring of Low Cell Voltage PFC Formation in 200 to 300 kA Aluminium Electrolysis Cells. In: 7th KIFEE, Kyoto

Bardai, A., Aga, B. E., Berveling, A., Droste, C., Fechner, M., Haugland, E., Karlsen, M., Liane, M., Ryman, S. O., Vee, T. H., Wedershoven, E. & Ovstetun, F. (2009) HAL 4e - Hydro's new generation cell technology. In: *Light Metals*.

Baudet, G. A documentary study on alumina extraction process, Service Geologique National (1977). <http://infoterre.brgm.fr/rapports/77-SGN-061-MIN.pdf>

Dancing, S.Y., Andreeva E.D., Pivovarov V.V. & al. Nepheline rocks are a complex aluminum raw material. - monograph. - Bowels. Moscow. (1988).

Dando, N. R., Xu, W., Nichols, R., Rusche, S. & Nemie, M. (2008) Comparison of PFC Emission Rates for Operation and Newly Started Pots at a Horizontal Stud Soderberg Smelter. In: *Light Metals*, ed. D. DeYoung, pp. 233-237.

Dando, N., Xu, W. & Marks, J. (2009) Comparison of PFC Emissions for Operation and Newly Started Pots at the ALCOA Fjardaal Point Fed Prebake Smelter. In: *Light Metals*, ed. G. P. Bearne, pp. 269-273.

Dando, N. R., Menegazzo, N., Espinoza-Nava, L., Westendorf, N. & Batista, E. (2015) Non anode effects PFC : Measurement consideration and potential impact. In: *Light Metals*, pp. 551-555. Orlando.

Dion, L., Marks, J., Kiss, L.I., Poncsak, S., Lagacé, C-L., (2017) Quantification of perfluorocarbon emissions during high voltage anode effects using non-linear approach. In: *Journal of Cleaner Production*, **164**: 357-366.

Dion, L., Wong, D. S., Nunez, P., Gaboury, S. & Spirin, A. V. (2018a) Evaluation of time consistency when quantifying emissions of perfluorocarbons resulting from low voltage anode effects. In: *Light Metals*, Phoenix, AZ, USA.

Dion, L., Gaboury, S., Picard, F., Kiss, L. I., Poncsak, S. & Morais, N. (2018b) Universal Approach to Estimate Perfluorocarbons Emissions During Individual High-Voltage Anode Effect for Prebaked Cell Technologies. *JOM*.

Emirates Global Aluminium. (2017) Reduction Cell Technologies. URL <https://www.ega.ae/en/technology/reduction-cell-technologies/>.

Hosterman, John W., Patterson, Sam H., & Good, Elizabeth E. World Nonbauxite Aluminum Resources Excluding Alunite, U.S. geological survey professional paper, 1076-C, Washington, (1990).

IAI (2000). International Aluminium Institute, International Aluminium Institute (2000) 'Life Cycle Assessment of Aluminium'

IAI (2001). International Aluminium Institute, Perfluorocarbon Emissions Reduction Programme 1990 - 2000, 2001, available at <http://www.world-aluminium.org/iai/publications/documents/pfc2000.pdf>.

IAI (2005a). International Aluminium Institute, The Aluminium Sector Greenhouse Gas Protocol, [http://www.world-aluminium.org/environment/climate/ghg\\_protocol.pdf](http://www.world-aluminium.org/environment/climate/ghg_protocol.pdf), 2005.

IAI (2005b). International Aluminium Institute, survey on composition of production materials, 2005 (unpublished)

IAI (2005c). International Aluminium Institute, Annual Anode Effect Survey 2003, [www.world-aluminium.org](http://www.world-aluminium.org), 2005.

IAI. (2006) The aluminium sector greenhouse gas protocol. 65 pages.

Layner, A.I. Alumina production. Textbook for higher educational institutions. Metallurgizdat. Moscow. (1961).

Loginova, I.V., Kirichikov, A.V., Alumina production. Textbook of Ural Polytechnic University. Ekaterinburg, (2010).

Maltais, J.-N., Ross, J., Marcoux, A. & Gaudreault, G. (2010) Application of a Method for the Determination of PFC Emissions During Aluminium Pot Start-up. In: *Light Metals*, pp. 271-276.

## Second-order Draft

- 2602 Marks, J. & Bayliss, C. (2012) GHG measurement and inventory for aluminium production. In : *Light Metals*, pp.  
2603 805-808.
- 2604 Marks, J. & Nunez, P. (2018a) Updated Factors for Calculating PFC Emissions from Primary Aluminum  
2605 Production. In: *Light Metals*, Phoenix, AZ.
- 2606 Marks, J. & Nunez, P. (2018b) New Algorithm for Calculating CF<sub>4</sub> Emissions from High Voltage Anode Effects.  
2607 In: *Light Metals*, Phoenix.
- 2608 Ni, L.P.. Alkaline hydrochemical methods for processing high-silicon bauxites. Science, Alma-Ata, Bibliography,  
2609 pp. 134-138 (1967)
- 2610 Ni, L.P. & Rayzman V.L. Combined ways of processing low-quality aluminum raw materials. Monograph,  
2611 Science, Alma-Ata, Bibliography, pp. 252-253 (1988).
- 2612 O Connor, D.J. Alumina Extraction from Non Bauxitic Materials. Germany, Aluminium Verlag, 1988 (385 p.)
- 2613 Rio Tinto Alcan. (2013) AP Technology - Our products and services. URL [https://www.ap-](https://www.ap-technology.com/SitePages/products.aspx)  
2614 [technology.com/SitePages/products.aspx](https://www.ap-technology.com/SitePages/products.aspx).
- 2615 Reny, P., Segatz, M., Leder, F.-M., Midtun, O. J., Hop, J. G. & Gikling, H. (2016) Low Energy Start-Up for Low  
2616 Energy Cells. In: *International Committee for Study of Bauxite, Alumina & Aluminium*, Quebec city.
- 2617 Smirnov, M. N. Physical-chemical fundamentals of alumina production from nepheline, Proceedings of the Second  
2618 International Symposium of ICSOBA, Vol. 3 pp. 337-345 (1971)
- 2619 Smirnov, V. Alumina Production in Russia Part I: Historical Background, JOM, 48 (8) (1996), pp. 24-26.
- 2620 Tabereaux, A. (2004) Anode effects and PFC emissions rates. In: *8th australasian aluminium smelting technology*  
2621 *conference*.
- 2622 US Environmental Protection Agency & International Aluminium Institute. (2008) Protocol for Measurement of  
2623 Tetrafluoromethane (CF<sub>4</sub>) and Hexafluoroethane (C<sub>2</sub>F<sub>6</sub>) Emissions from Primary Aluminum Production. 42  
2624 pages.
- 2625 Wong, D. & Marks, J. (2013) Continuous PFC emissions measured on individual 400 kA cells. In: *Light Metals*,  
2626 pp. 865-870. San Antonio.
- 2627 Wong, D. S., Fraser, P., Lavoie, P. & Kim, J. (2015) PFC emissions from detected versus nondetected anode  
2628 effects in the aluminium industry. *JOM* **67**(2): 342-353.
- 2629 Chen, X., Li, W., Zhang, Y., Qiu, S. & Bayliss, C. (2013) Investigation on formation mechanism of non-anode  
2630 effect related PFC emissions from aluminum reduction cells. In: *TMS Light Metals*, pp. 877-881.
- 2631 Zarouni, A. A., Reverdy, M., Zarouni, A. & Vankatasubramaniam, K. G. (2013) A study of low voltage PFC  
2632 emissions at DUBAL. In: *Light Metals*, pp. 859-863. San Antonio.
- 2633
- 2634 **SECTION 4.8**
- 2635 Cai, B., Liu, H., Kou, F., Yang, Y., Yao, B., Chen, X., Wong, D. S., Zhang, L., Li, J., Kuang, G., Chen, L., Zheng,  
2636 J., Guan, D. & Shan, Y. (2018) Estimating perfluorocarbon emission factors for industrial rare earth metal  
2637 electrolysis. *Resources, Conservation and Recycling* **136**: 315-323.
- 2638 International Aluminium Institute. (2006) The Aluminium Sector Greenhouse Gas Protocol. 65 pages.
- 2639 Kingsnorth, D. J. (2015) The Global Rare Earths Industry Today - Plagued by Illegal Production in China". In:  
2640 *11th International Rare Earths Conference*, Singapore.
- 2641 Kjos, O. S., Solheim, A., Aarhaug, T., Osen, K. S., Martinez, A. M., Sommerseth, C., Gudbrandsen, H., Støre, A.  
2642 & Gaertner, H. (2018) PFC Evolution Characteristics During Aluminium and Rare Earth Electrolysis. In: *Light*  
2643 *Metals 2018*, pp. 1449-1455.
- 2644 Liu, K.-r., Chen, J.-s. & Wei, X.-j. (2001) Analysis of anodic gases in neodymium electrolysis. *The Chinese*  
2645 *Journal of Nonferrous Metals* **11**(6): 1118-1120.
- 2646 US Environmental Protection Agency & International Aluminium Institute. (2008) Protocol for Measurement of  
2647 Tetrafluoromethane (CF<sub>4</sub>) and Hexafluoroethane (C<sub>2</sub>F<sub>6</sub>) Emissions from Primary Aluminum Production. 42  
2648 pages.

- 2649 Vogel, H., Flerus, B., Stoffner, F. & Friedrich, B. (2017) Reducing Greenhouse Gas Emission from the  
2650 Neodymium Oxide Electrolysis. Part I: Analysis of the Anodic Gas Formation. *Journal of Sustainable*  
2651 *Metallurgy* **3**(1): 99-107.
- 2652 Vogel, H. & Friedrich, B. (2015) Development and Research Trends of the Neodymium Electrolysis – A Literature  
2653 Review. In: *8th European Metallurgical Conference (EMC)*, Dusseldorf, Germany.
- 2654 Vogel, H. & Friedrich, B. (2018) An estimation of PFC emissions by rare earth electrolysis. In: *Light Metals*,  
2655 Phoenix.
- 2656 Wen, H., Kuang, G. & Mao, J. (2004) Circular 10 kA molten salt electrolyzer for preparing rare earth metal. In:  
2657 ed. China's State Intellectual Property Office, pp. 1-7. China: Ganzhou Keli Rare Earth New Materials Co.,  
2658 Ltd.
- 2659 Wen, H., Kuang, G. & Mao, J. (2012) 25 KA rare earth electrolytic cell for fluoride molten salt system. In: ed.  
2660 China's State Intellectual Property Office, pp. 1-6. China.
- 2661 Zhang, L., Wang, X. & Gong, B. (2018) Perfluorocarbon emissions from electrolytic reduction of rare earth metals  
2662 in fluoride/oxide system. *Atmospheric Pollution Research*.
- 2663