

CHAPTER 4

METAL INDUSTRY EMISSIONS

[Parts in yellow – comments from Authors]

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

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4 METAL INDUSTRY EMISSIONS

4.1 INTRODUCTION

No Refinement

4.2 IRON & STEEL AND METALLURGICAL COKE PRODUCTION

The production of iron and steel leads to emissions of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). This chapter provides guidance for estimating emissions of CO₂ and CH₄.¹

- The iron and steel industry broadly consists of:
- Primary facilities that produce both iron and steel;
- Secondary steelmaking facilities;
- Iron production facilities; and
- Offsite production of metallurgical coke.

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

In some countries, there will be coke production facilities that are not integrated with iron and steel production (i.e., ‘offsite’). This chapter provides guidance for estimating emissions of CO₂ and CH₄ 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:

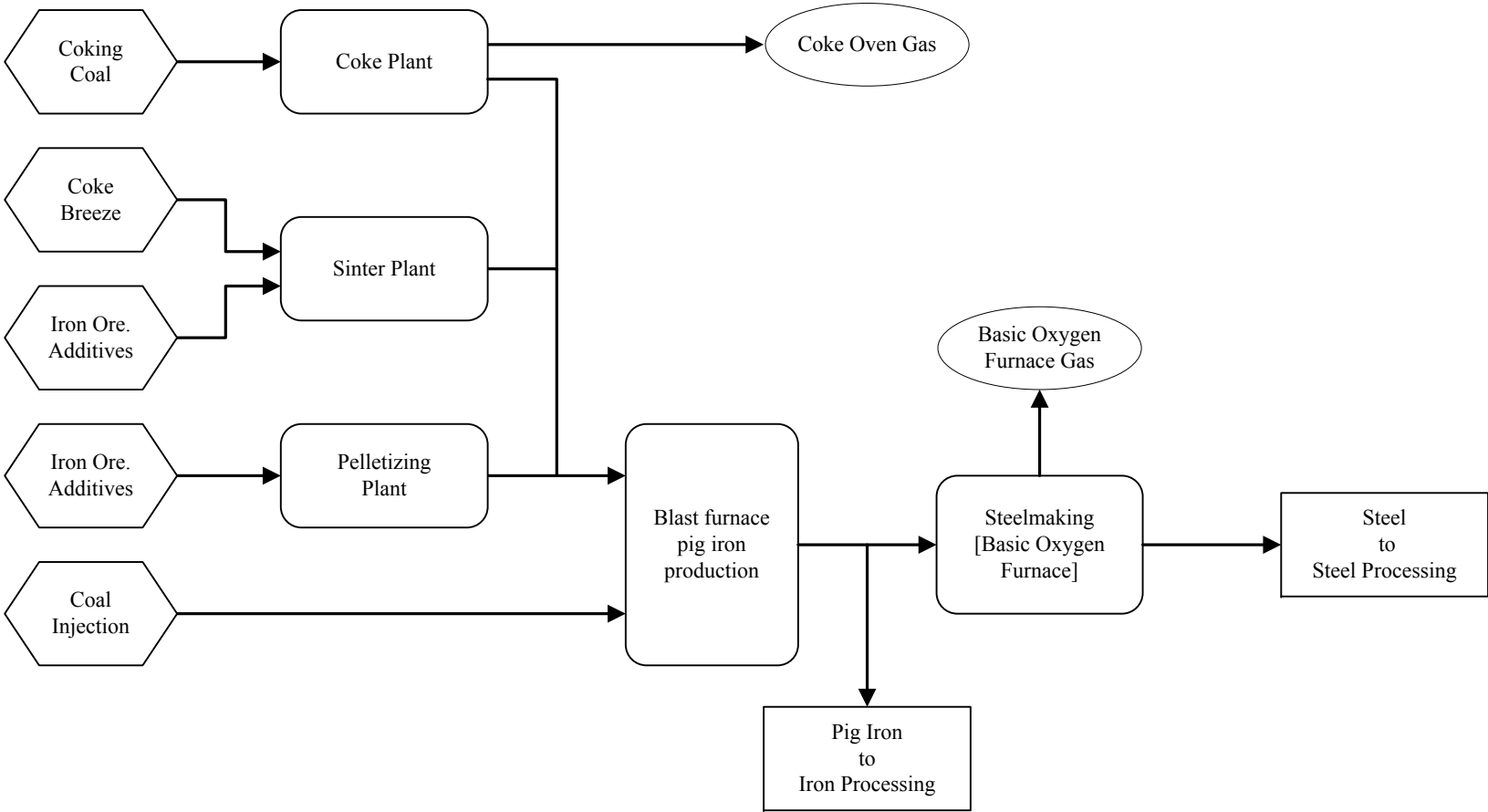
Iron production can occur onsite at integrated facilities or at separate offsite facilities containing blast furnaces and BOFs. In addition to iron production via blast furnace, iron can be produced through a direct reduction process. Direct reduction involves the reduction of iron ore to metallic iron 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).

¹ No methodologies are provided for N₂O emissions. These emissions are likely to be small, but countries can calculate estimates provided they develop country-specific methods based on researched data.

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



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

4.2.1 Introduction

No Refinement

4.2.2 Methodological issues

This section, 4.2.2, is an update/elaboration of section 4.2.2 Chapter 4, Volume 3 of 2006 IPCC Guidelines and should be used instead of the section 4.2.2 Chapter 4, Volume 3 of 2006 IPCC Guidelines

4.2.2.1 CHOICE OF METHOD: METALLURGICAL COKE PRODUCTION

This section outlines three tiers for calculating CO₂ emissions and two tiers for calculating CH₄ emissions from metallurgical coke production¹. The emissions should be reported under the Energy Sector Category 1Acii Manufacture of Solid fuels, but the methodology is presented here due to the significant overlap of the activity data used for iron and steel production GHG methodological calculations.

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 CO₂ emissions. For CH₄ emissions, the decision tree is presented in Figure 4.8.

The Tier 1 method to estimate CO₂ emissions comprises two approaches, depending on the type of activity data available:

- Tier 1 a: If only metallurgical coke production data is available, the methodology is based on the use of a default emission factor given in Table 4.1
- 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. In many countries, the statistics related to these data are available and regularly updated, so the collection of these data should not represent a serious obstacle. For Tier 1 this is the preferred method.

The Tier 2 method to estimate CO₂ emissions is based on a carbon mass balance approach, using national statistical data of the carbonaceous materials inputs and outputs from coke production process. If country-specific carbon content data derived from national fuel characteristics are available, it is *good practice* to use them. Otherwise, default carbon content data provided in Table 4.1 should be used.

The Tier 3 method to estimate CO₂ emissions requires plant-specific emissions measurement data, combined with plant-specific activity data and plant/country-specific carbon content data for carbon mass balance approach, when measurements are not available.

Table 4.1a summarizes the necessary activity data and emission factors that inventory compilers will use to estimate CO₂ emissions and assess the consistency of each tier with those indicated for stationary combustion in the Energy Sector.

¹ No methodologies are provided for N₂O. These emissions are likely to be small, but countries can develop country-specific methods based on researched data.

TABLE 4.1A TIERS TO ESTIMATE CO ₂ EMISSION FACTORS FROM METALLURGICAL COKE PRODUCTION				
Tier		Activity data	Emission factor	Consistency with the Energy Sector
Tier 1	Tier 1 a	Metallurgical coke produced in the country	Default EF (Table 4.1)	Not consistent
	Tier 1 b	Metallurgical coal consumed and coke produced (simplified carbon balance approach with COG assumption of 100% combusted in coke production)	Default carbon content (Table 4.1)	Consistent with Tier 1 <i>Preferred method</i>
Tier 2		National data on the carbonaceous materials and fuels consumed and produced (carbon mass balance approach)	Default carbon content (Table 4.3)	Consistent with Tier 1
			Country-specific carbon content	Consistent with Tier 2 <i>Preferred method</i>
Tier 3		Plant-specific data on quantity and quality of carbonaceous materials and fuels consumed and C outputs produced (carbon mass balance approach)	Plants/Country- specific carbon content	Consistent with Tier 3
		Measurement emissions data		

Fugitive emissions

Depending on the type of sources, metallurgical coke oven plants present two types of emissions:

- direct emissions that are discharged to the atmosphere through stacks¹, and
- fugitive emissions, that occurs during regular or irregular operation, related with the transportation of coke, , ascension pipes, coke pushing, quenching and leakages at the battery². These emissions are difficult to quantify.

Tier 1a for CO₂ considers default emission factors derived from stack measurements from both coke oven technology types, and therefore includes only direct emissions. If the country chooses this approach the corresponding CO₂ fugitive emissions should be estimated following the methodology described in Volume 2 section 4.3.3 (category 1B1c) of 2019 Guidelines Refinement.

Tiers 1.b, 2 and 3 based on carbon mass balance include both direct and fugitive emissions. If the country estimate CO₂ emissions using this approach, should not estimate CO₂ fugitive emissions as described in Volume 2 section 4.3.3 (category 1B1c) of 2019 Guidelines Refinement, in order to avoid double counting.

Flaring

Some facilities use flaring under routine conditions or as emergency systems. In integrated facilities is usual to burn coke oven gas jointly with blast furnace gas and other gases produced, such as converter gas. The methodologies to estimate the corresponding GHGs emissions are presented in Volume 2 chapter 2 of 2019 Guidelines Refinement.

¹ For by-products recovery technology route that means the coqueification process emissions plus off-gas from battery heating, and for non-recovery by-products technology route that means coqueification process emissions, where COG is totally combusted around the batteries ovens.

² Specific door emissions vary widely depending upon the type of doors, the size of ovens and the quality of maintenance. Maintenance can be a determining factor. (IPPC, 2013)

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TIER 1 METHOD**Tier 1 a: Production based method**

Applying this method requires the amount of tonnes of coke produced in the country and the use of a default emission factor, given in Table 4.1. The following equation is used:

$$\begin{aligned} &\text{EQUATION 4.1} \\ &\text{EMISSIONS FROM COKE PRODUCTION (TIER 1A)} \\ &E_{CO_2, energy} = Coke \bullet EF_{CO_2} \text{ and } E_{CH_4, energy} = Coke \bullet EF_{CH_4} \end{aligned}$$

Where:

$E_{CO_2, energy}$ or $E_{CH_4, energy}$ = emissions of CO₂ or CH₄ from coke production, in kg CO₂ or kg CH₄, to be reported under the Energy Sector, category 1.A.1c.

Coke = quantity of coke produced nationally, tonnes

EF= emission factor, tonnes CO₂/tonne coke production or tonnes CH₄/tonne coke production, Table 4.1

Tier 1 b: Simplified carbon balance method

Tier 1b 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:

$$\begin{aligned} &\text{EQUATION 4.1A} \\ &\text{CO}_2 \text{ EMISSIONS FROM METALLURGICAL COKE PRODUCTION (TIER 1B)} \\ &E_{CO_2, energy} = [CC \bullet C_{CC} - CO \bullet C_{CO}] \bullet \frac{44}{12} \end{aligned}$$

Where:

$E_{CO_2, energy}$ = CO₂ emissions to be reported in the Energy Sector category 1.A.1c (kg)

CC = quantity of coking coal consumed for coke production in the country (kg)

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

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

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

TIER 2 METHOD

The Tier 2 method to estimate CO₂ emissions is appropriate if national statistics on process inputs and outputs from integrated and non-integrated coke production processes are available. The following equation with a default carbon content given in Table 4.3, is used:

$$\begin{aligned} &\text{EQUATION 4.2A} \\ &\text{CO}_2 \text{ EMISSIONS FROM ONSITE COKE PRODUCTION (TIER 2)} \\ &E_{CO_2, energy} = \left[CC \bullet C_{CC} + \sum_a (PM_a \bullet C_a) + BG \bullet C_{BG} \right. \\ &\quad \left. - CO \bullet C_{CO} - COG \bullet C_{COG} - \sum_b (COB_b \bullet C_b) \right] \bullet \frac{44}{12} \end{aligned}$$

Where:

$E_{CO_2, energy}$ = CO₂ emissions to be reported in the Energy Sector category 1.A.1c (kg)

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

PM_a = 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_b = quantity of coke oven by-product *b* produced, and transferred either offsite or to other facilities (kg), including flaring.

C_x = default carbon content of material input or output *x*, (kg C / kg material)

Note: CO₂ emissions from flaring are deducted in the carbon mass balance because the corresponding emissions are estimated with the methodology described in Volume 2 chapter 2 of 2019 Guidelines Refinement.

There is no Tier 2 method to estimate CH₄ emissions from metallurgical coke production.

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.

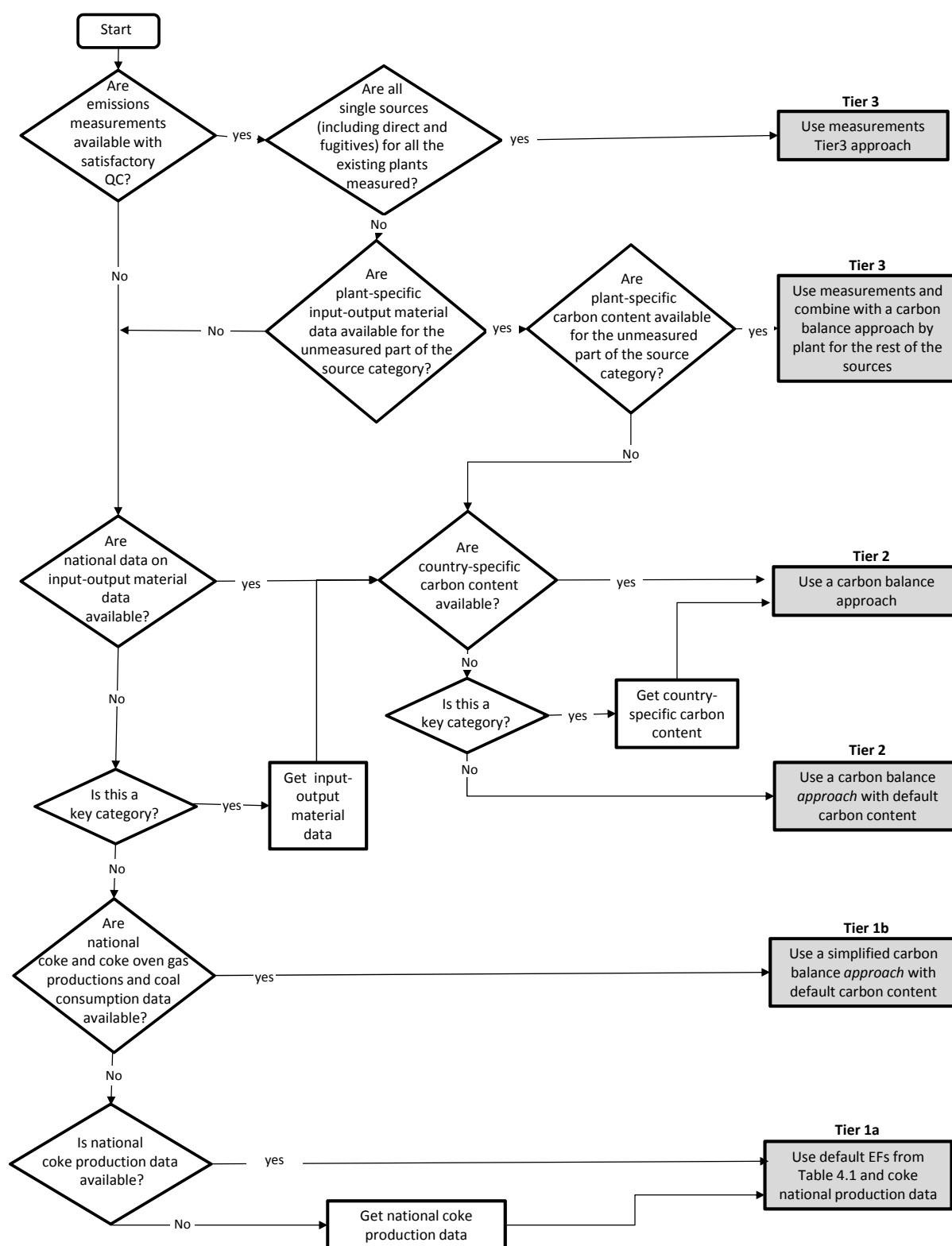
Tier 3 comprises two approaches for CO₂ and only one for CH₄:

- For CO₂ and CH₄: monitoring data of direct and fugitive sources.
- For CO₂: carbon mass balance approach, with plant-specific carbon content of all the materials used and produced.

If actual measured CO₂/CH₄ emissions data are available from all direct single sources present in all the coke production plants in the country, these data can be aggregated and used directly to account for 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 Guidelines Refinement.

It is necessary to distinguish between direct emissions and fugitive emissions: while direct emissions should be reported under Energy Sector, category 1A_{ii} Manufacture of Solid fuels, fugitive emissions should be reported under Energy Sector category 1.B.1c Fugitive Emissions from Fuel Transformation.

If facility-specific CO₂ emissions data are not available for part or for the total sources of the country, the CO₂ emissions for the unmeasured sources can be estimated from plant-specific activity data applying a carbon mass balance with country specific carbon content, applying Equation 4.3.

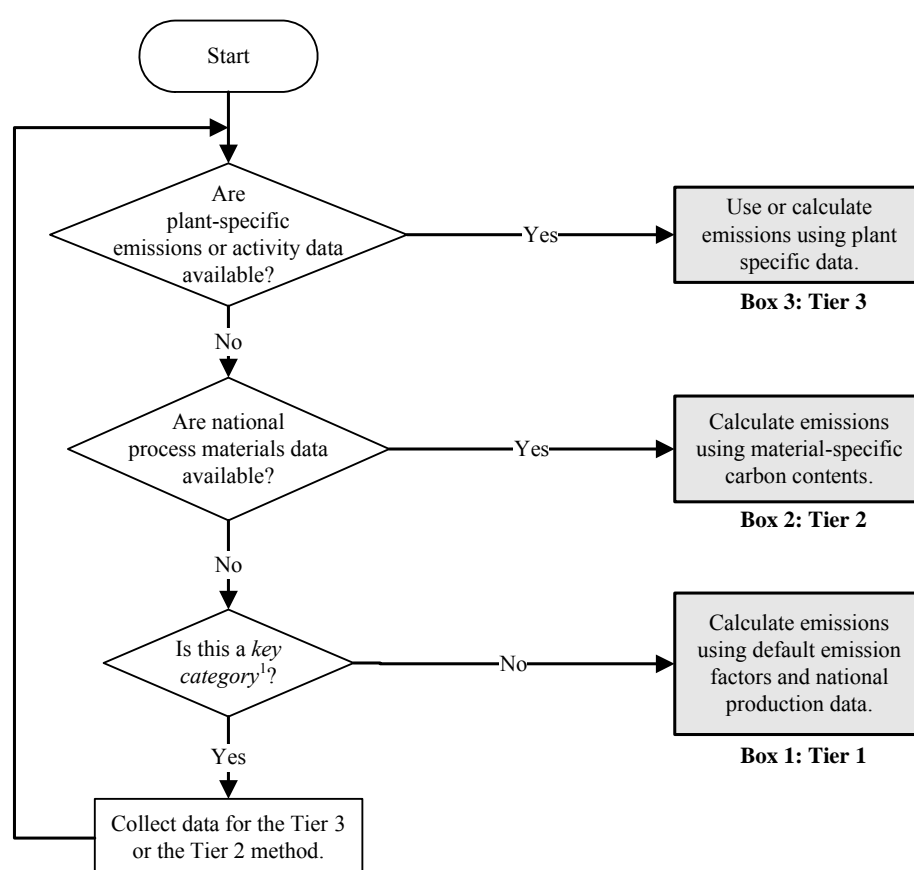
Figure 4.6 Estimation of CO₂ emissions from metallurgical coke production

4.2.2.2 CHOICE OF METHOD: IRON AND STEEL PRODUCTION

This section outline three tiers for calculating CO₂ emissions and two tiers for calculating CH₄ emissions from iron and steel production.

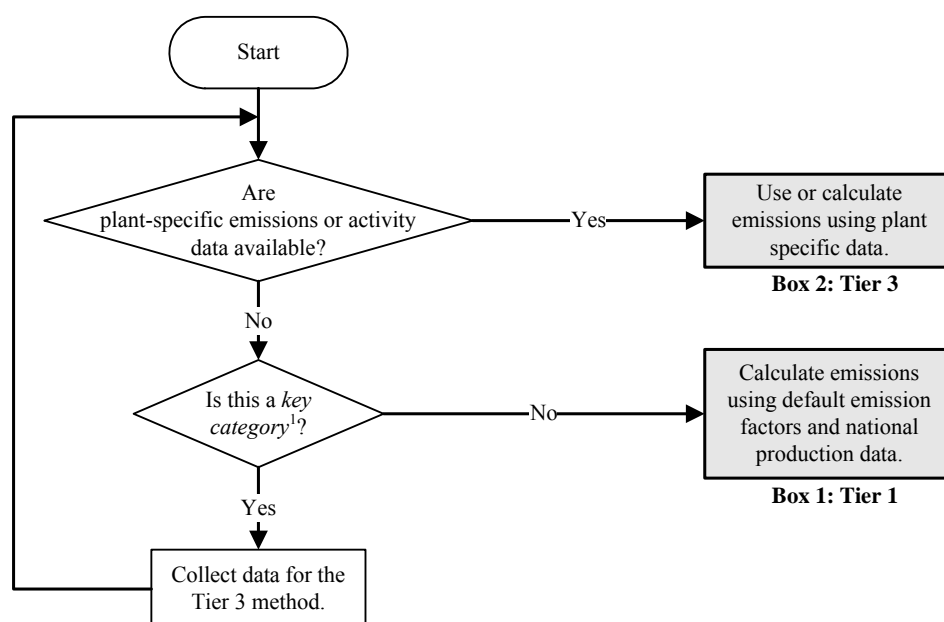
Decision Tree for Estimation of CO₂ Emissions from Iron & Steel Production and Decision Tree for Estimating of CH₄ Emissions from Iron and Steel Production. The Tier 1 method is based on national production data and default emission factors. It may lead to errors due to its reliance on assumptions rather than actual data for the quantity of inputs into the sinter production and iron and steel production sector that contribute to CO₂ emissions. Therefore, the Tier 1 is appropriate only if iron and steel production is not a *key category*. Default emission factors are provided for sinter production, blast furnace iron making, direct reduced iron production, pellet production, and each method of steelmaking. The primary sources of emissions are the blast furnace iron making, and steelmaking. The Tier 2 method for estimating CO₂ emissions from iron and steel production is based on data for the known consumption of raw materials, including reducing agents, and industry-wide data. It uses a mass balance approach and material-specific carbon contents. The Tier 2 method is not applicable to estimating CH₄ emissions. The Tier 3 method requires plant-specific emissions or activity data aggregated to the national level for estimating CO₂ and CH₄ emissions.

Figure 4.7 Decision tree for estimation of CO₂ 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 Decision tree for estimation of CH₄ 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 CO₂ 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 CO₂ emissions from production of Direct Reduced Iron (DRI) for the Tier 1 method using a CO₂ 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

CO₂ EMISSIONS FROM IRON AND STEEL PRODUCTION (TIER 1)

$$\text{Iron \& Steel: } E_{\text{CO}_2, \text{non-energy}} = \text{BOF} \cdot EF_{\text{BOF}} + \text{EAF} \cdot EF_{\text{EAF}} + \text{OHF} \cdot EF_{\text{OHF}}$$

EQUATION 4.5

CO₂ 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

CO₂ 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

CO₂ EMISSIONS FROM SINTER PRODUCTION (TIER 1)

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

EQUATION 4.8

CO₂ 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 CO₂ 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 CO₂/tonne x produced

Tier 2 method

The Tier 2 method is appropriate if the inventory compiler has access to national data on the use of process materials for iron and steel production, sinter production, pellet production, and direct reduced iron production. In addition, as discussed in Section 4.2.2.5, there are 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 estimate than the Tier 1 method because it takes into account the actual quantity of inputs that contribute to CO₂ emissions.

The methodology to estimate emissions from pellet production, energy consumption and heating value and carbon content of the fuel can be used similarly to the other methodologies.

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EQUATION 4.9**CO₂ 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**CO₂ 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 CO₂ to be reported in IPPU Sector, tonnes

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

COB_a = quantity of onsite coke oven by-product *a*, consumed in blast furnace, tonnes.

CI = quantity of coal directly injected into blast furnace, tonnes

L = quantity of limestone consumed in iron and steel production, tonnes

D = quantity of dolomite consumed in iron and steel production, tonnes

CE = quantity of carbon electrodes consumed in EAFs, tonnes

O_b = quantity of other carbonaceous and process material *b*, consumed in iron and steel production, such as sinter or waste plastic, tonnesCOG = quantity of coke oven gas consumed in blast furnace in iron and steel production, m³ (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, m³ (or other unit such as tonnes or GJ. Conversion of the unit should be consistent with Volume 2: Energy)C_x = carbon content of material input or output *x*, tonnes C/(unit for material *x*) [e.g., tonnes C/tonne]

Where, for sinter production:

 $E_{CO_2, non-energy}$ = emissions of CO₂ 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, m³ (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, m³ (or other unit such as tonnes or GJ. Conversion of the unit should be consistent with Volume 2: Energy)PM_a = quantity of other process material *a*, other than those listed as separate terms, such as natural gas, and fuel oil, consumed for coke and sinter production in integrated coke production and iron and steel production facilities, tonnesSOG = quantity of sinter off gas transferred offsite either to iron and steel production facilities or other facilities, m³ (or other unit such as tonnes or GJ. Conversion of the unit should be consistent with Volume 2: Energy)C_x = carbon content of material input or output *x*, tonnes C/(unit for material *x*) [e.g., tonnes C/tonne]

In an integrated plant 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) and to produce electricity in an internal power plant to cover the internal needs, should be reported under IPPU (see Section 4.2.2.5). The methodology for that corresponds to those described in the Volume 2, chapter 2

Equation 4.11 calculates CO₂ 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

CO₂ 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 CO₂ 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

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 CO₂ emissions data are available from iron and steelmaking facilities, these data can be aggregated to account for national CO₂ emissions. If facility-specific CO₂ emissions data are not available, CO₂ 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 CH₄

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 CO₂ above the charge, in the hood and off-gas channels, but some will remain un-reacted as CH₄ and non-methane volatile organic compounds (NMVOC). The amounts depend on the operation of the furnace. Sprinkle-charging will reduce the amounts of CH₄ compared to batch-wise charging. Increased temperature in the hood (less false air) will reduce the content of CH₄ further.

This section describes a Tier 1 default method and a more advanced Tier 3 facility-level method for CH₄ from sinter production or iron production, both of which are similar to the approaches described for estimating CO₂ emissions. There is no Tier 2 method. CH₄ may be emitted from steel-making processes as well, however those emissions are assumed to be negligible. Therefore CH₄ emissions from steel-making processes are not discussed here.

The Tier 1 methodology for CH₄ is based on emission factors and national production statistics.

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EQUATION 4.12**CH₄ EMISSIONS FROM SINTER PRODUCTION (TIER 1)**

$$\text{Sinter Production: } E_{CH_4, non-energy} = SI \cdot EF_{SI}$$

EQUATION 4.13**CH₄ EMISSIONS FROM BLAST FURNACE PRODUCTION OF PIG IRON (TIER 1)**

$$\text{Pig Iron Production: } E_{CH_4, non-energy} = PI \cdot EF_{PI}$$

EQUATION 4.14**CH₄ EMISSIONS FROM DIRECT REDUCED IRON PRODUCTION (TIER 1)**

$$\text{Direct Reduced Iron Production: } E_{CH_4, non-energy} = DRI \cdot EF_{DRI}$$

Where:

 $E_{CH_4, non-energy}$ = emissions of CH₄ 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 CH₄/tonne x produced

The Tier 3 method uses plant specific emissions data. If actual measured CH₄ emissions data are available for coke production, these data can be aggregated to account for national CH₄ 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 CO₂ and CH₄ 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 centerline 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.

TABLE 4.1 TIER 1 DEFAULT CO₂ EMISSION FACTORS FOR COKE PRODUCTION AND IRON & STEEL PRODUCTION		
Process	Emission Factor	Source
Coke Oven: Non recovery of byproduct -USA (tonne CO ₂ per tonne coke produced)	1.23	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 (EPA, 2008a)
Coke Oven: By product recovery - USA (tonne CO ₂ per tonne coke produced)	0.21	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 (EPA, 2008a) and 2008 revision to EPA's Compilation of Emission Factors in AP-42. (EPA, 2008a)
Coke Oven: By product recovery – China (tonne CO ₂ per tonne coke produced)	0.52.	2009 value from “Determination of carbon dioxide emission factors in typical process for large iron-steel companies”.(Acta ScientiaeCircumstantiae, Aug.2013)
Coke Oven: By-product recovery technology – European countries (tonne CO ₂ per tonne coke produced)	0,5103 -0,5170 ⁽²⁾	The lower range value is to be applied for plants with less than 20 years. Older coke plants should apply the upper range value.
Sinter Production – European Countries (tonne CO ₂ per tonne sinter produced)	0.301-0.566 ⁽²⁾	The lower range value is to be applied for plants which do not use carbonate ores. Upper range value are to be applied in plants which do use carbonate ores. European IPPC Bureau (2013), Integrated Pollution Prevention and Control (IPPC) 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 3.4, Page 96 ⁽³⁾
Sinter Production - China (tonne CO ₂ per tonne sinter produced)	0.21	Chinese typical sintering process case. “Determination of carbon dioxide emission factors in typical process for large iron-steel companies”.(Acta ScientiaeCircumstantiae, Aug.2013)
Iron Production - China (tonne CO ₂ per tonne pig iron produced)	1.38	Determination of carbon dioxide emission factors in typical process for large iron-steel companies.(Acta ScientiaeCircumstantiae, Aug.2013)
Iron Production (tonne CO ₂ per tonne pig iron produced)	1.35	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, Tables 7.2 and 7.3. http://eippcb.jrc.es/pages/FActivities.htm
Direct Reduced Iron production (tonne CO ₂ per tonne DRI produced)	0.70	Direct Reduced Iron Production: European IPPC Bureau (2001), Integrated Pollution Prevention and Control (IPPC) Best Available Techniques Reference Document on the Production of Iron and Steel, December 2001, Table 10.1 Page 322 and Table 10.4 Page 331. http://eippcb.jrc.es/pages/FActivities.htm
Pellet production (tonne CO ₂ per tonne pellet produced)	0.03	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. http://eippcb.jrc.es/pages/FActivities.htm

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TABLE 4.1 (CONT.) TIER 1 DEFAULT CO ₂ EMISSION FACTORS FOR COKE PRODUCTION AND IRON & STEEL PRODUCTION		
Steelmaking Method		
Basic Oxygen Furnace (BOF) (tonne CO ₂ 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 ₂ per tonne of steel produced)*1	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 ₂ 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 ₂ 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 ₂ 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>(1) The average value from the literature range is used as default EF (0,510 tCO₂ /t coke). This is justified as the range is very wide based on the type of fuel gases used for firing oven batteries.</p> <p>(2) Note that these EF represent the sum of CO and CO₂ emissions, as CO oxidises and becomes CO₂</p> <p>(3) The average value from the literature range is used as default EF (0,265 tCO₂ /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 tCO₂ / t sinter) is very wide based on the type of fuel gases used for ignition oven.</p> <p>(4)</p> <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 CO₂ 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 CO₂ emissions from blast furnace iron making. The Tier 1 CO₂ emission factor for EAFs in this table is therefore not applicable to EAFs that use pig iron as a raw material.</p>		

Methane emission factors

Default CH₄ emission factors are provided in Table 4.2 below. The Tier 1a CH₄ emission factor for coke production is derived from plant-specific CH₄ emissions data from stacks and quenching towers for different EU Member States and complemented by other references.

The Tier 1a CH₄ emission factor for sinter production is derived by averaging plant-specific CH₄ emissions data for European sinter plants reported in the EMEP/CORINAIR Emissions Inventory Guidebook (EEA, 2005) and in other emission inventory reports. Emissions of CH₄ are reported in Table 8.2a of the EMEP/CORINAIR Emission Inventory Guidebook for sinter and palletising plants. For sinter plants using coke breeze an emission factor of 50 mg CH₄ per MJ was reported and a range of coke input of 38 to 55 kg coke per tonne sinter was reported. This corresponds to an average emission factor of 0.07 kg CH₄ per tonne sinter using the default value of 28.2 TJ/Gg coke. An emission factor of 0.05 kg CH₄ per tonne sinter was reported for sinter plants operating in Finland. (Pipatti, 2001)

TABLE 4.2 TIER 1 DEFAULT CH ₄ EMISSION FACTORS FOR COKE PRODUCTION AND IRON & STEEL PRODUCTION		
Process	Emission Factor	Source
Coke Production (g CH ₄ 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	[To be completed]	

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 Volume 2, Chapter 1. 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.

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TABLE 4.3 TIER 2 MATERIAL-SPECIFIC CARBON CONTENTS FOR IRON & STEEL AND COKE 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
EAFF Carbon Electrodes ¹	1.00
EAFF coal	0.89
Heavy oil	0.793
Light oil	0.709
Kerosene	0.677
LPG	0.814
Hot Briquetted Iron ²	0.02
Limestone	0.121
Natural Gas	0.549
Oxygen Steel Furnace Gas	0.412
Petroleum Coke ²	0.87
Purchased Pig Iron	0.047
Scrap Iron ²	0.04
Steel ²	0.01
Source: Notes:	
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 ₂ to C (multiplied by 12/44).	
* The amount of CO ₂ emissions from charcoal can be calculated by using this carbon content value, but it should be reported as zero in national greenhouse gas inventories. (See Section 1.2 of Volume 1.)	

4.2.2.4 CHOICE OF ACTIVITY DATA

TIER 1 METHOD

The Tier 1 method requires only the amount of steel produced in the country by process type, the total amount of pig iron produced that is not processed into steel, and the total amount of coke, direct reduced iron, pellets, and sinter produced; in this case the total amount of coke produced is assume to be produced in integrated coke production facilities. These data may be available from governmental agencies responsible for manufacturing statistics, business or industry trade associations, or individual iron and steel companies. If a country only has aggregate data available, a weighted factor should be used. Total crude steel production is defined as the total output of usable 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 CO₂ 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 CO₂ emissions) or on plant-specific direct emissions monitoring data (for both CO₂ and CH₄ emissions). In this case, 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 Guidelines 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 CO₂ 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**

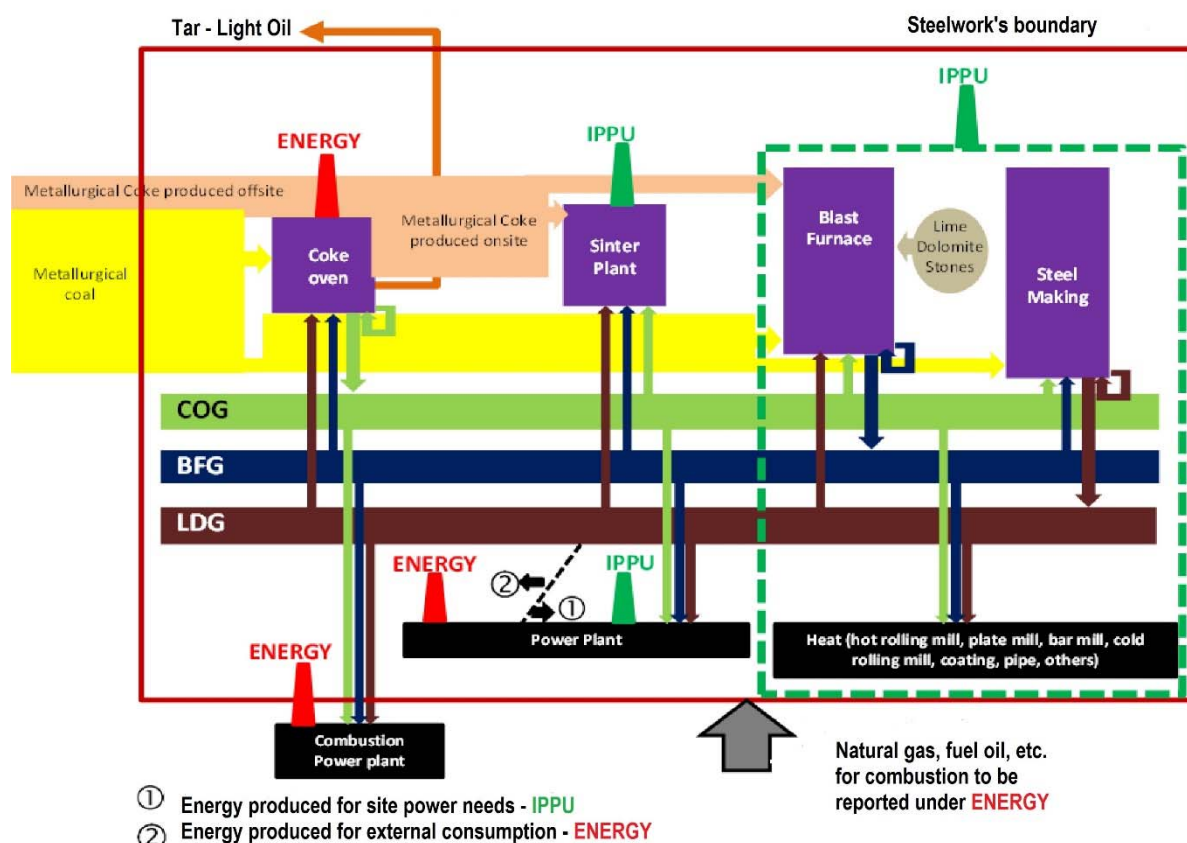
Iron and steel production consists of many production processes (facilities), such as coking, sintering, blast furnace, steelmaking, and rolling process. These processes are connected to each other by the pipeline network, which carries by-product gases, such as coke oven gas, blast furnace gas and basic 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 CO₂ 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 CO₂ 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 Volume 3, Box 1.1, page 1.8 of 2019 Guidelines Refinement). 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 for metallurgical coke production should be reported under Energy.
- The emissions from flaring should be reported under Energy, Volume XXX

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Figure 4.8A Energy or IPPU CO₂ 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 CO₂ emissions and energy intensity of steelworks, and to conduct continuous data collection for tracking performance and for promoting international cooperation in CO₂ reduction. World Steel Association has established such method in 2007, and since then, has been conducting yearly CO₂ 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 CO₂ 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 CO₂ emissions data (Reference ISO 14404). The net CO₂ emissions and production from a steel plant are calculated using all the parameters within the boundaries. The CO₂ emission intensity is calculated by the net CO₂ emission from the plant using the boundaries divided by the amount of crude steel production of that plant. With this methodology, the CO₂ 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 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 CO₂ efficiency.

There is a difference between 2019 Guidelines Refinement and ISO 14404, related with CO₂ 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 CO₂ and CH₄ emissions. If the coke fines are produced at a coke plant within the facility and the CO₂ and CH₄ emissions are accounted for in the coal entering the facility, or if the coke breeze is otherwise accounted for as purchased coke, the CO₂ and CH₄ 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 BOF off-gas as energy in the energy sector as sources of CO₂, 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 CO₂ 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 BOF 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 CO₂ from metallurgical coke production and Tier 2 or 3 to estimate CO₂ 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 used of Tier 1 to estimate CO₂ from iron and steel production and Tier 2 or 3 to estimate CO₂ 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 CO₂ emissions from integrated iron and steel plants.

ELECTRODE CONSUMPTION

Electrode consumption amounts to about 3.5 kg/tonne for EAF furnaces. However, depending upon the characteristics of the charged materials, some carbon may be added to the EAF (typically about 20 kg/tonne) for process control purposes or may be contained in the charged materials themselves as iron substitutes, an increasingly more frequent trend. In these cases, CO₂ and CH₄ 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 CO₂ or CH₄ emissions from this steelmaking process.

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OHF PROCESS

Although the OHF is no longer prevalent, it may be necessary to inventory CO₂ and CH₄ 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 *2006 IPCC Guidelines* and should be used instead of the section 4.2.3 Chapter 4, Volume 3 of *2006 IPCC Guidelines*

The default emission factors for coke production and iron and steel production used in Tier 1 may have an uncertainty of ± 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 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 ₂ and CH ₄ 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 ± 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 ± 5 percent uncertainty. Tier 3 uncertainty may be more accurately derived based on an analysis of the actual data received

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

No refinement

4.2.4.1 REPORTING AND DOCUMENTATION

No refinement

765 **4.3 FERROALLOY PRODUCTION**

766 No refinement

767

768

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 instead of 4.4 Chapter 4, Volume 3 of the 2006 IPCC Guidelines

4.4.1 Introduction to Primary Aluminium

This section covers process emissions from primary aluminium production including alumina refining using the Bayer-Sinter and Nepheline ore technology¹. 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 from the mining of aluminium-containing ore, bauxite. Most of this bauxite is refined through the Bayer process which extracts alumina (aluminium oxide) 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.

Molten aluminium is extracted from the alumina by the Hall-Heroult electrolytic process. In this process, electrolytic reduction cells differ in form, and configuration of the carbon anode and alumina feed system and are typically grouped by technology accordingly. Previously four technology types were defined: Centre-Worked Prebake (CWPB), Side-Worked Prebake (SWPB), Horizontal Stud Søderberg (HSS) and Vertical Stud Søderberg (VSS). 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, and as such, the technology types have been redefined as follows:

- (i) *Legacy Point Fed Prebake (PFPB_L)* – lines operating with older cell designs with line currents of less than 350kA and with fewer than 24 anodes;
- (ii) *Modern Point Fed Prebake (PFPB_M)* – new cell technologies² including: AP3X/AP4X, APXe/AP60, EGA DX and DX+, and, generally newer technology cells that operate at line currents in excess of 350kA and/or with 24 or more anodes;
- (iii) *Modern Point Fed Prebake without fully automated anode effect intervention strategies for PFC emissions (PFPB_{MW})* – new cell technologies operating with large cells with line currents in excess of 350kA, 24 or more anodes and with no automatic anode effect intervention capacity (refer to Box Description below);
- (iv) *Side-Worked Prebake (SWPB)*
- (v) *Horizontal Stud Søderberg (HSS) technology*; and
- (vi) *Vertical Stud Søderberg (VSS) technology*.

¹ 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.

² Details on some of these newest cell technologies are available on the following references: 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*, Rio Tinto Alcan. (2013) AP Technology - Our products and services. URL <https://www.ap-technology.com/SitePages/products.aspx>, Emirates Global Aluminium. (2017) Reduction Cell Technologies. URL <https://www.ega.ae/en/technology/reduction-cell-technologies/>.

Box 4.2

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 re-establish 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_{MW})* – where anode effects are largely terminated through manual operator intervention and can result in higher PFC emissions.

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

- (i) Carbon dioxide (CO₂) 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) Perfluorocarbons (PFCs) emissions of CF₄ and C₂F₆ during anode effects (for which refinements for aluminium smelting are included in the following sections).

Also emitted are smaller amounts of process emissions, CO, SO₂, and NMVOC. SF₆ is not emitted during the electrolytic process and is only rarely used in the aluminium manufacturing process, where small quantities are emitted when fluxing specialized high magnesium aluminium alloys.

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 at a minimum level 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 CO₂ EMISSIONS FROM PRIMARY ALUMINIUM PRODUCTION

No refinement

4.4.2.2 CHOICE OF EMISSION FACTORS FOR CO₂ EMISSIONS FROM PRIMARY ALUMINIUM PRODUCTION

No refinement

4.4.2.3 CHOICE OF METHOD FOR PFCs

BOX 4.3

HIGH AND LOW VOLTAGE 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 voltage to be elevated above the normal operating range; however, PFC gases can also be generated without elevated 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 is determined as 8 volts (Tabereaux 2004; US Environmental Protection Agency & International Aluminium Institute 2008).

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

During electrolysis, alumina (Al_2O_3) is dissolved in a fluoride melt comprising about 80 weight percent cryolite (Na_3AlF_6). Perfluorocarbons (PFCs) are formed from the reaction of the carbon anode with the cryolite melt during a process upset condition known as an 'anode effect'. 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 identified based on a sudden increase in voltage of generally greater than 8V (US EPA & IAI, 2008) for a period of around 3 seconds or similar (Tabereaux 2004). These anode effects are now known as a high voltage anode effects (HVAE). Since the late 2000s, driven by the development of more productive, high amperage cell technology with many large anodes, low voltage anode effects (LVAE) CF_4 emissions were 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. These LVAE emissions have been largely omitted from inventories to date but are nonetheless likely to be widespread and as such, methodologies are now included as to ensure GHG inventories are as complete as possible. Reference to *total PFC emissions* is HVAE and LVAE 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 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, in turn 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 cover the methods with reference to the slope model only. If the overvoltage method is still used, it should be adopted at the Tier 3 level only.

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, 2018). This takes into account technology or plant specific performance at the HVAE level, respectively. There is currently no generally recognised means to calculate LVAE CF_4 emissions from the process control data that is normally recorded during primary aluminium production as data related to LVAE are not typically included. The most accurate approach to date is to continuously measure both LVAE and HVAE PFC emissions, but this is not widely or regularly practiced to support inventory development. Moreover, there is no official methodology to standardise the measurement and calculation of the LVAE PFC 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.

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 (tbc) 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 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 individual facility anode effect performance, which is the key determinant of anode effects and thus PFC emissions, are 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.

EQUATION 4.25A HVAE PFC EMISSIONS (TIER 1 METHOD)

$$E_{CF_4} = \sum_i (EF_{CF_4,i} \bullet MP_i)$$

and

$$E_{C_2F_6} = \sum_i (EF_{C_2F_6,i} \bullet MP_i)$$

Where:

E_{CF_4} = emissions of CF₄ from aluminium production, kg CF₄

$E_{C_2F_6}$ = emissions of C₂F₆ from aluminium production, kg C₂F₆

$EF_{CF_4,i}$ = default emission factor by cell technology type *i* for CF₄, kg CF₄/tonne Al

$EF_{C_2F_6,i}$ = default emission factor by cell technology type *i* for C₂F₆, kg C₂F₆/tonne Al

MP_i = metal production by cell technology types, tonnes Al

Tier 1 method for Low Voltage Anode Effect (LVAE) emissions

The Tier 1 method for LVAE emissions uses technology-based default emission factors for the main production technology types (Legacy PFPB, Modern PFPB, Modern PFPB without automated controls, Side Worked Prebake, Vertical Stud Søderberg and Horizontal Stud Søderberg). PFC emissions can be calculated according to Equation 4.25B. The level of uncertainty in the Tier 1 method is much greater because individual facility HVAE performance, which is considered a proxy of overall process control, are 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.

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EQUATION 4.25B
LVAE PFC EMISSIONS (TIER 1 METHOD)

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

Where:

LVAE E_{CF_4} = low voltage anode effect emissions of CF_4 from aluminium production, kg CF_4 $EF_{LV_{CF_4,i}}$ = default emission factor for LVAE by cell technology type i for CF_4 , kg CF_4 /tonne Al MP_i = metal production by cell technology type i , tonnes Al

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

The equation for estimating individual plant HVAE CF_4 emissions is based on the relationship between anode effect 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_4 and C_2F_6 , the two gases should be considered together when estimating PFC emissions. C_2F_6 emissions are calculated in all the HVAE methods described herein as a fraction of CF_4 emissions.

With an established relationship between anode effect process data and PFC emissions, process data collected on an on-going basis can be used to calculate PFC emissions in lieu of direct measurement of PFCs. Equation 4.27 should be used when anode effect minutes per cell day are recorded. For individual high voltage anode effects, the reported anode effect duration 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. Then the anode effects minutes per cell day 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 represents the kg of CF_4 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 4.26A describes the method for both CF_4 and C_2F_6 .

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

$$E_{CF_4} = S_{CF_4} \bullet AEM \bullet MP$$

and

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

Where:

 E_{CF_4} = emissions of CF_4 from aluminium production, kg CF_4 $E_{C_2F_6}$ = emissions of C_2F_6 from aluminium production, kg C_2F_6 S_{CF_4} = slope coefficient for CF_4 , (kg CF_4 /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 C_2F_6/CF_4 , kg C_2F_6 /kg CF_4

TBD: Tier 2b and Tier 3b method for High Voltage Anode Effect (HVAE) emissions: Based on individual anode effect measurement

(Research to be presented at TMS 2018 conference: Marks and Nunez, 2018 and Dion et al. 2018 – methodologies are undergoing testing and development & may be included in Second Order Draft)

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 2018). 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 4.26B LVAE PFC EMISSIONS (TIER 2 AND TIER 3 METHODS)

$$LVAE_E_{CF_4} = \sum (E_{CF_4,i} * ER_{LV\ CF_4,i} * MP_i)$$

Where:

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

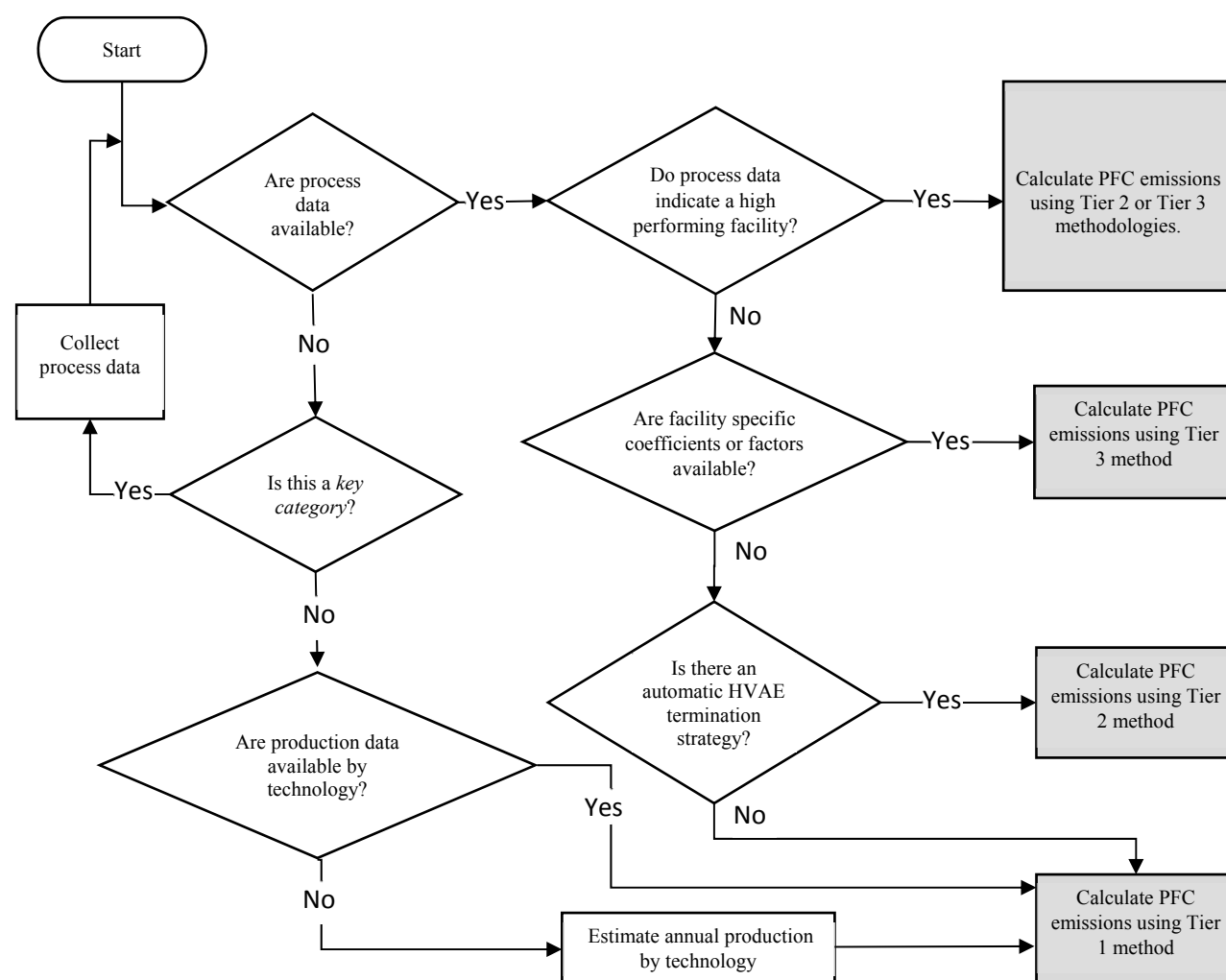
E_{CF_4} = high voltage anode effect emissions of CF_4 from aluminium production by cell technology i , kg CF_4

$ER_{LV\ CF_4}$ = Ratio of LVAE/HVAE CF_4 emissions, either default ratio by cell technology type i (Tier 2) or smelter specific emission ratio (Tier 3), kg CF_4 /tonne Al

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

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Figure 4.12 **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 Tier 1 method are provided in Table 4.15.

TABLE 4.15 TECHNOLOGY SPECIFIC DEFAULT EMISSION FACTORS FOR THE CALCULATION OF HAVE AND LVAE EMISSIONS FROM ALUMINIUM PRODUCTION (TIER 1 METHOD)						
Technology	HVAE				LVAE	
	CF ₄		C ₂ F ₆		CF ₄	
	EF _{CF₄} (kg/tonne Al)	Uncertainty Range (%) ^b	EF _{C₂F₆} (kg/tonne Al)	Uncertainty Range (%)	EF _{CF₄} (kg/tonne Al)	Uncertainty Range (%) (tbd)
PFPB _L	0.029	-88/+234	0.001	-93/+208	0.016	
PFPB _M	0.030	-88/+226	0.001	-91/+217	0.018	
PFPB _{MW}	0.161 ^a	-85/+476	0.005 ^a	-98/+478	-	-
SWPB	0.391	-76/116	0.093	-89/+68	0.010	
VSS	0.210	95/+447	0.011	-95/+412	0.001	
HSS	0.503	-79/+112	0.033	-76/+86	0.026	
Notes:						
^a includes LVAE emissions						

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

The Tier 2 slope method 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 TECHNOLOGY SPECIFIC COEFFICIENTS FOR THE CALCULATION OF HAVE PFC EMISSIONS FROM ALUMINIUM PRODUCTION USING SLOPE ¹ METHODOLOGY (TIER 2 METHOD)				
Technology	CF ₄		Weight Fraction C ₂ F ₆ /CF ₄	
	EF _{CF₄} (kg/tonne Al) _a	Uncertainty Range (%) _b	C ₂ F ₆ /CF ₄	Uncertainty (%)
PFPB _L	0.127	-33/+58	0.114	-72/+174
PFPB _M	0.104	-27/+32	0.057	-55/+55
PFPB _{MW} ^a	-	-	-	-
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
Notes:				
^a 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.				

¹ The overvoltage method is not very widely used anymore within the industry. Therefore there is insufficient data available to update the overvoltage coefficients respective to the overvoltage methodology. Good practices recommend compiling PFC inventories by using the slope model for recent and future calculations. However, satisfying results are still expected by using the overvoltage method along with Tier 3 coefficients (Dion et al. 2017; Marks & Bayliss 2012) and it should not be excluded if Tier 3 slope coefficients are unavailable.

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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 4.16A. Median ratios are recommended for PFPB technologies as very high LVAE/HVAE ratios in the measurement dataset skewed the average ratio significantly.

TABLE 4.16A TECHNOLOGY SPECIFIC DEFAULT EMISSION FACTORS FOR THE CALCULATION OF LVAE PFC EMISSIONS FROM ALUMINIUM PRODUCTION (TIER 2 METHOD)		
Technology	Emissions Ratio of LVAE/HVAE	Uncertainty (tbd)
	ER_{CF4}	
PFPB _L	0.400 ^a	
PFPB _M	0.752 ^a	
PFPB _{MW}	-	
SWPB	0.104	
VSS	0.058	
HSS	0.054	
^a median value is used for default ratios due to outliers skewing weighted average (e.g. start-up conditions)		

Tier 3: PFC emission factor 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.

TBD: Tier 2b and Tier 3b method for High Voltage Anode Effect (HVAE) emissions: Based on individual anode effect measurement
(Research to be presented at TMS 2018 conference: Marks and Nunez, 2018 and Dion et al 2018)

4.4.2.5 CHOICE OF ACTIVITY DATA

Production statistics should be available from every facility to enable use of Tier 1 methods for both CO₂ and PFC emissions. Uncertainty in the tonnes of aluminium produced is likely to be low in most countries. Given the expected universal availability of production data, production capacity data should only be used as a check on production statistics.

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

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

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

For CO₂ emissions, all aluminium smelters collect data to support Tier 2 or Tier 3 methods. Søderberg smelters collect anode paste consumption data while Prebake smelters record baked anode consumption. The Tier 2 and Tier 3 methods use the same equation for calculation of CO₂ emissions; however, the Tier 3 method uses facility specific composition data for anode materials while the Tier 2 method uses industry average anode composition data.

4.4.2.6 COMPLETENESS

No refinement

4.4.2.7 DEVELOPING A CONSISTENT TIME SERIES

PFC EMISSIONS RESULTING FROM HIGH VOLTAGE ANODE EFFECTS

A complete time series of PFC related activity data such as high voltage anode effect (HVAE) minutes per cell day or overvoltage gives the best time series results. Because PFC emissions only became a major focus area in the early 1990s for the global aluminium industry, some facilities may have limited information about the required anode effect data to implement Tier 2 or Tier 3 PFC inventory practices over the entire time covered by the inventory. Substantial errors and discontinuities can be introduced by reverting to Tier 1 methods for PFC emissions for years for which activity data are not available. The appropriateness of applying Tier 2 or Tier 3 PFC emission factors back in time to a given facility and availability of detailed process data vary with the specific conditions. Generally, backcasting of Tier 2 or Tier 3 methods using splicing or surrogate data are preferred over use of Tier 1 emission factors. Specifically, where only high voltage anode effect frequency data are available and high voltage anode effect duration data are unavailable, it is *good practice* to splice or backcast PFC emissions per tonne aluminium based on high voltage anode effect frequency data. When going back in time using Tier 2 methodologies, it is important to take into consideration the reported change in slope coefficient for high voltage anode effects. Hence, it is suggested that inventory compilers use the respective emission factors from the 2006 IPCC guidelines for annual inventories up to 2006 with any of the two suggested method. However, for 2007 and up, good practices are to use the slope model, with the emission factors reported in the 2019 refinements.

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

Currently many facilities are making PFC measurements that facilitate implementation of Tier 3 PFC inventory methods. There are a number of issues that impact on whether Tier 3 PFC emission factors can be extrapolated to past inventory periods. Factors that should be considered include whether any technology upgrades have been implemented at the facility, including significant amperage increase or new cell control system, whether there have been substantial changes in work practices affecting the distribution of the anode effect durations, whether any 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 helpful information on splicing methods and details regarding constructing a time series for primary aluminium is available from IAI (International Aluminium Institute 2006). Expert advice is also available from the International Aluminium Institute (London, UK) 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 (Wong & Marks 2013; Xiping et al. 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 by using the respective Tier 2 coefficient specific to each category. 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

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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.* 2018) 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.* 2018).

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 ± 5 percent for both the Tier 2 and Tier 3 methods, and less than ± 10 percent for the Tier 1 method. The reactions leading to carbon dioxide emissions are well understood and the emissions are very directly connected to the tonnes of aluminium produced through the fundamental electrochemical equations for alumina reduction at a carbon anode and oxidation from thermal processes. Both of these fundamental processes producing carbon dioxide are included in process parameters routinely monitored at the production facilities, the net carbon consumed and/or paste consumption. The main source of uncertainty is in the net carbon consumed for Prebake technologies and paste consumption for 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.

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 CO₂ 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 in Table 4.15. 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 primary aluminium, the EPA/IAI Protocol for Measurement of Tetrafluoromethane (CF₄) and Hexafluoroethane (C₂F₆) Emissions from Primary Aluminum Production is the internationally recognized standard (US Environmental Protection Agency & International Aluminium Institute 2008). **Inventory compilers should encourage plants to use this method for developing Tier 3 PFC equation coefficients. [TBD – an ongoing work on LV PFCs].** 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. 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.

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 PFCs¹ 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

¹ Reference to PFCs from this section applies to both HVAE and LVAE emissions.

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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 CF₄ and C₂F₆ 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.

TABLE 4.17 GOOD PRACTICE REPORTING INFORMATION FOR CALCULATING CO₂ AND PFC EMISSIONS FROM ALUMINIUM PRODUCTION BY TIER			
Data	Tier 3	Tier 2	Tier 1
PFCs			
Annual national production (by CWPB, SWPB, HSS, or VSS technology)			X
Annual production by smelter (by CWPB, SWPB, HSS, or VSS technology)	X	X	
Anode Effect minutes per cell-day or Anode Effect Overvoltage (mV)	X	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
CO₂			
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		

[TBD – The Table 4.17 copied from the 2006 IPCC Guidelines, but might need updating for the 2019 Refinement for Aluminium+Alumina Production]

4.4.5 Methodological issues for alumina production

This sub-section, 4.4.5, is a new guidance in Section 4.4 Chapter 4 Volume 3 of 2019 Refinement and it is not included in Section 4.4 Chapter 4 Volume 3 of 2006 IPCC Guidelines

This guidance does not consider any new methodological issues associated with greenhouse gas emissions inventories for the production of alumina from the Bayer process. The emissions from the Bayer process, are covered by 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 only (NP) are considered in this section (see Figure X).

4.4.5.1 ALUMINA REFINING PROCESSES

BAYER-SINTERING PROCESS

In 2017, it is estimated that about 5 % of global alumina production was via by the Bayer-sintering process. The process is used instead of the more conventional Bayer process when the bauxite feed has a high silica content that makes its processing by 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 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” alumina (Al₂O₃), which is the basic raw material for primary aluminium production.

Depending on bauxite quality there two variations of the Bayer-Sintering processes: *parallel* and *sequential*. In the case of the parallel process part of bauxite (up to 20-30%) is processed in sintering branch and rest is processed by pure Bayer process. In the case of sequential process, 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 greenhouse gases emissions CO₂, NO₂, CH₄ from the Bayer- sinter process are listed below, of which, sintering, is the main focus of this Section:

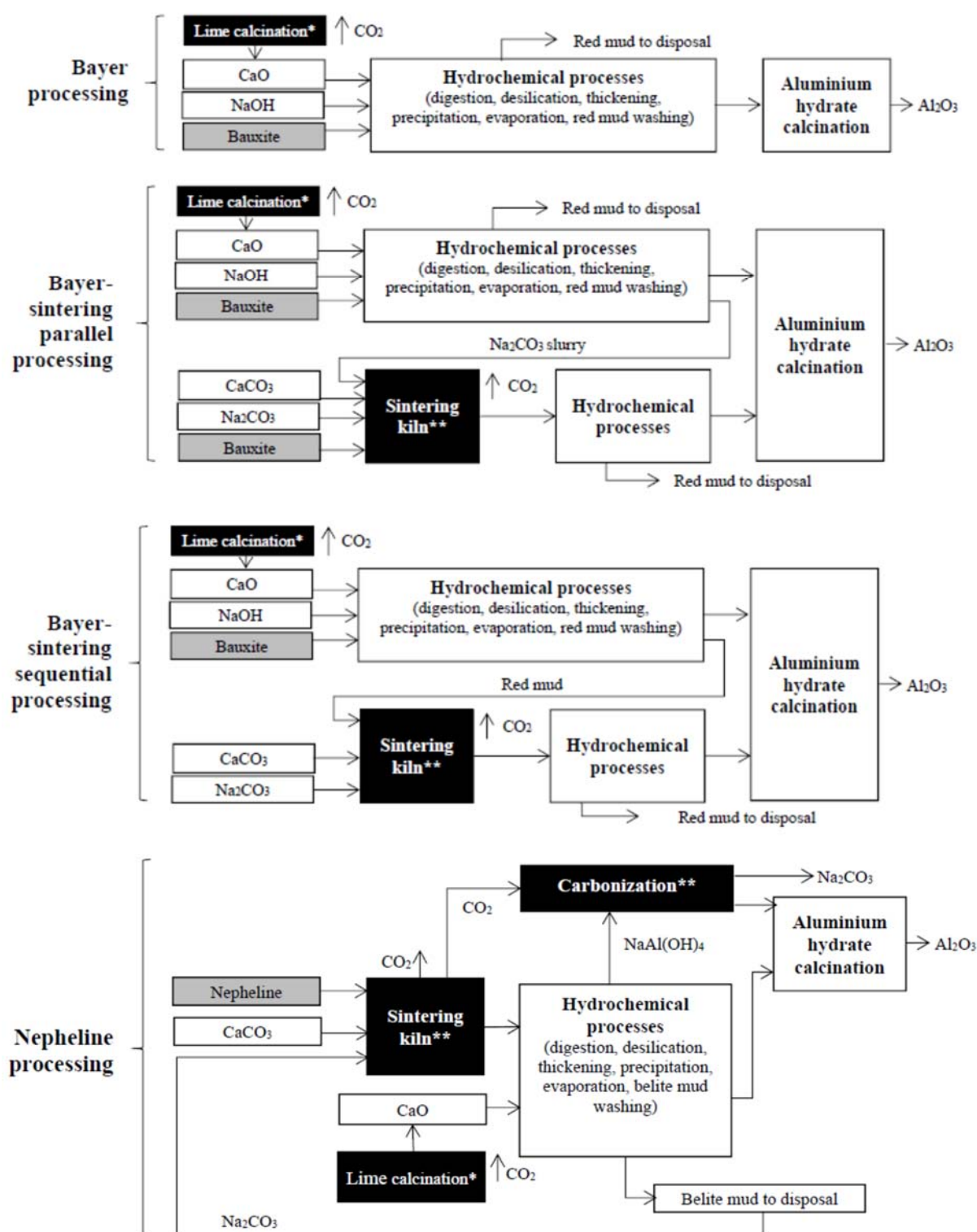
- *Sintering* (fuel burning and carbonates decomposition)¹
- Power and heat production facilities (fuel burning)²
- Alumina hydrate calcination (fuel burning)⁸
- Lime calcination (fuel burning and carbonates decomposition)³

¹ Calculation of GHG emissions shall be done in accordance to Volume 2 Energy, Chapter 2 Stationary combustion for fuel burning. Emissions from carbonate decomposition shall be calculated in accordance to Section 4.4.5.2 of current Chapter..

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

³ Calculation of GHG emissions shall be done in accordance to Volume 3 Industrial Processes and Product Use, Chapter 2 Mineral industry emissions, Section 2.3 Lime production.

Figure 4.12A 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 current Chapter..

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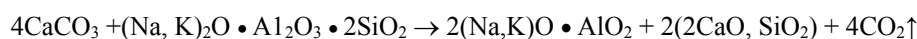
NEPHELINE PROCESS

Nepheline ore is a sodium and potassium containing aluminosilicate that contains more silica than alumina. In order to make silica insoluble at leaching process, it is combined with lime forming $2\text{CaO} \bullet \text{SiO}_2$ (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: crushing and milling of nepheline with limestone and recycled soda liquor in ball mills forming the raw mix; sintering of raw mix (at about 1300°C) in rotary kilns where calcium carbonate is decomposed and the reaction between calcium oxide and nepheline takes place.

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The nepheline sinter is leached with the dissolution of alkali aluminate. The sinter residue is separated and transported to cement production and the aluminate liquor is passed on for desilication to remove partially dissolved silica from liquor. Then, alumina hydrate is obtained from the green liquor partly by decomposition and partly by carbonisation. Carbonisation is a sink of CO_2 in the process.

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 nepheline process are similar to the Bayer-sintering process but since there are many by-products produced alongside alumina, (belite mud for cement, soda ash, potash), the emissions of CO_2 shall be split between output products.

OTHER GHG SOURCES AND SINKS

CO_2 and CH_4 is also produced during other sub-processes but the emissions from such processes are currently considered to be negligible and not a main source of GHG emissions (>1 percent (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 CO_2 sinks to consider:

- Carbonization
- CO_2 absorption through use of lime or bauxite residue for flue gas desulphurization
- CO_2 absorption through use of water collected from bauxite/nepheline storage residue area.
- CO_2 absorption through reaction of residue deposits with atmosphere over time

Of these sinks, only CO_2 absorption through reaction of residue deposits with atmosphere over time is considered insignificant (>1 percent (expert opinion)). Significant CO_2 sinks related to the alumina refining process are considered in the new guidance for Tier 2 and 3 methods for emissions from the sintering process (Section 4.4.5.2).

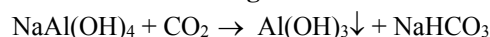
As noted throughout Volume 3 on Industrial Processes and Product Use (IPPU), the emission estimation methodologies outlined in this Chapter consider only process-related emissions and do not consider energy-related

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 CO₂ emissions from fuel consumed in Lime calcination, Sintering, Alumina hydrate calcination and Electricity and heat production at own boilers, CHP or power plants should be considered using the guidance related to the combustion of fossil fuels.

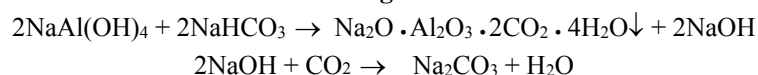
CO₂ sink from carbonization process in nepheline process

The main reactions of CO₂ capture by during carbonization process are:

Stage 1



Stage 2



Part of CO₂ after Sintering is going through gas treatment facilities to remove particles and other harmful components and forwarding to carbonizators, where carbonization is proceeding step by step.

In practice, two-stage carbonization is required since towards the end of the operation when but a few grams per liter of alumina remain in the solution, not alumina hydrate but sodium hydroaluminocarbonate Na₂O · Al₂O₃ · 2CO₂ · nH₂O is formed which would contaminate alumina hydrate with alkali.

The first stage of carbonization ends at concentrations of 3-4 g/l of Al₂O₃. Alumina hydrate is then separated and the second stage of carbonization is carried on to sodium hydrocarbonate concentrations of 10-15 g/l of NaHCO₃. The precipitate is sodium hydroalumocarbonate as mentioned above since the carbonate-containing solutions are further processed to yield sodium carbonate and potassium carbonate, they must not contain more than 0.1-0.15 g/l of Al₂O₃. It is for this reason that carbonization must be carried on up to 10-15 g/l of NaHCO₃ concentrations since the solubility of the alumocarbonate is sharply reduced in the presence of substantial amounts of hydrocarbonate.

CO₂ absorption through use of lime

The quick lime (CaO) used in the Bayer process, initially produced from limestone (CaCO₃), can partially recombine inadvertently with atmospheric CO₂ into calcium carbonate.

As use of lime is shared between numerous industrial processes, acceptance of this CO₂ sink at national level should be checked. Some guidance is given in workbooks related to the Australian GHG inventory, which indicates a default rate of 12% for the fraction of lime used which re-combines in the Bayer process.

In some refineries, a "waste lime" component of the residue stream (red lime) can be isolated and used in certain lime applications. If such by-products are used within the scope 1 boundary, additional credits should be allowed by adding their lime content to the Bayer lime consumption before calculation of absorbed CO₂. If such by-products are used for flue gas desulphurization CO₂ absorption through use of lime or bauxite residue for flue gas desulphurization should apply rather. If they are sold, credits should only be allowed under scope 3.

If a refinery uses lime or bauxite residue (e.g. red lime) to treat flue gas to remove sulphur dioxide, it should be assumed that the scrubbing system will remove also some CO₂ in the flue gas with 35% efficiency, unless actual data on the particular scrubbing system efficiency for CO₂ is available.

An option is making direct measurement of CO₂/CO in flue gas where such scrubbing system is used. Any difference with the CO₂ calculated should be attributed to the CO₂ removal efficiency.

CO₂ 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 is containing a lot of sodium alkaline to treat flue gas to remove particles, SO₂ and other acid gases it should be assumed that the scrubbing system will remove also some CO₂ in the flue gas. The efficiency of CO₂ capture is very depends on concentration of sodium alkaline in circulating water and type of scrubbing technology. In case of lack of direct

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measurement data of CO₂/CO in flue gas where such scrubbing system is used it is recommended do not consider CO₂ removal in CO₂ calculations.

CO₂ absorption through bauxite residue neutralization

Carbonation of bauxite residue (red mud) can be carried out to utilize the capacity of this waste to capture carbon dioxide and reciprocally the capacity of CO₂ to neutralize the highly alkaline red mud. The absorption of CO₂ is rapid and can be efficient if there is good contact between the residue and the carbon dioxide. For high concentration CO₂ 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 carbon dioxide recorded as an increase in bicarbonate alkalinity.

For lower concentrations of CO₂ such as flue gas where concentrations may be 12-15%, the reaction efficiency will be reduced. If CO₂ removal data is not available for bauxite residue contacted with gases containing less than 50% CO₂, then it is recommended that reaction efficiency of 35% be assumed by default.

CO₂ absorption can be estimated by multiplying the quantity of CO₂ 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 CO₂ actually absorbed in the neutralization process.

As mentioned in «CO₂ and methane emissions from organic carbon in bauxite», when residue is neutralized using CO₂, the biological activity in the residue deposit and in the collected leachate increases dramatically, and can produce carbon dioxide or methane. 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 4.14 describes *good practice* in choosing the most appropriate method based on national circumstances. In the Tier 1 method, emissions are based on alumina production data. 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.

For Tier 1, emissions are estimated using alumina production data and national or default emission factors for the relevant technologies. The Tier 2 approach is a calculation based on the mass balance approach of all carbonate inputs and outputs, the emission factors for the carbonates, and the fraction of calcination achieved. For the Tier 2 approach, technology specific default factors are specified. The Tier 3 approach relies on plant specific data.

Tier 2 and 3 methods should also include a correction for emissions of dust. Tier 3 also includes a correction addition for emissions associated with dust not recycled to the kiln. Any uncalcined dust not recycled to the kiln should be subtracted from the total emissions estimate.

Should CO₂ capture technology be installed and used at a plant, it is *good practice* to deduct the CO₂ captured in a higher tier emissions calculation. The default assumption is that there is no CO₂ capture and storage (CCS) taking place. Any methodology taking into account CO₂ capture should consider that CO₂ 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 CO₂ are not double counted. In these cases, the total amount of CO₂ captured should preferably be reported in the corresponding energy combustion and IPPU source categories in proportion to the amounts of CO₂ generated in these source categories. For additional information on CO₂ capture and storage refer to Volume 3, Section 1.2.2 and for more details on capture and storage to Volume 2, Section 2.3.4.

TIER 1 METHOD

The Tier 1 method for **lime production** emissions is described in (Volume 3, Section 2.3.1.1). 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** 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 is dependent on the quality of bauxite and the silica content of the bauxite. A high silica content, low content of Al_2O_3 in ore leads to use high carbonate content.

If detailed and complete data (including weights and composition) for the carbonate(s) consumed in the sintering and lime production processes are not available (Tier 2 and 3), 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 4.27A:

$$\text{CO}_2 \text{ Emissions} = M_{\text{Al}_2\text{O}_3} \cdot S_{\text{Al}_2\text{O}_3} \cdot EF_{\text{SintAl}_2\text{O}_3}$$

Where:

$\text{CO}_2 \text{ Emissions}$ = emissions of CO_2 from sintering production, tonnes

$M_{\text{Al}_2\text{O}_3}$ = weight (mass) of alumina produced, tonnes

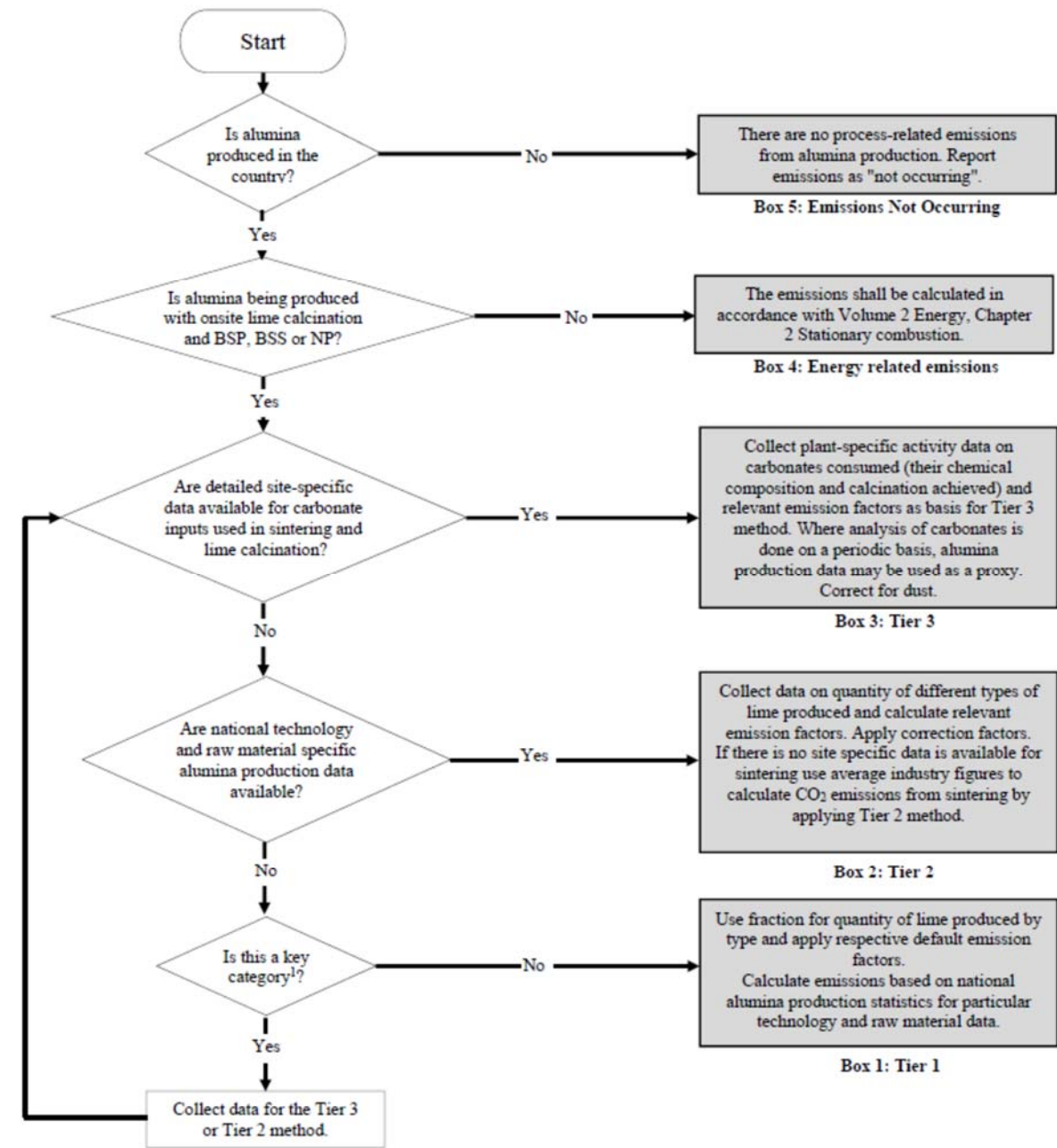
$S_{\text{Al}_2\text{O}_3}$ = share of alumina produced by sintering process. The parameter can be varied from more than 0 to 1, where 1 is related to 100% of alumina produced by sintering process.

$EF_{\text{SintAl}_2\text{O}_3}$ = emission factor for sintering, tonnes CO_2 /tonne alumina (see discussion under Section 4.4.5.3 Choice of Emission Factors for Tiers 1 and 2), which is not corrected for dust.

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

- (iii) The share of alumina produced by sintering process rather than the leaching process is stable over the years.
- (iv) In case of alumina production from the nepheline ore, 100 percent of alumina is produced with the sintering process;
- (v) Plants are generally able to control the CaCO_3 content of the raw material inputs and output of sintering process within close tolerances;
- (vi) The CaCO_3 content of the raw materials inputs from a given plant tends not to change significantly over the years;
- (vii) The main source of the CaO for most plants is CaCO_3 and, at least at the plant level, any major noncarbonated 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 **Decision tree for estimation of CO2 emissions from alumina production**



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

TIER 2 AND 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 Tier 2 or 3 approach described in of Chapter 2, Section 2.

For Sintering processes, CO₂ 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 2 method makes use of typical industry values for impurities while the Tier 3 method uses actual concentrations of impurities. The choice of method between the Tier 2 and Tier 3 method will depend on whether the appropriate data are available at the individual plant level.

Tier 3 is based on the collection of disaggregated data on the types (compositions) and quantities of carbonates consumed in the sintering process at particular plant, as well as the respective emission factors of the carbonates consumed. Emissions are then calculated using Equation 4.27B. The Tier 3 approach includes an adjustment to subtract any uncalcined carbonate within sintering kiln dust (SKD) 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 CO₂ 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 make an effort to see if they are included in the Energy Sector. Currently, however, too few data exist on the kerogen or carbon contents of non-fuel raw materials for mineral processes to allow a meaningful default value related to the average kerogen content of raw materials to be provided in this chapter. For plant-level raw material-based calculations (Tier 3) where the kerogen content is high (i.e., contributes more than 5 percent of total heat), it is *good practice* to include the kerogen contribution to emissions.

The Tier 3 approach will likely only be practical for individual plants and countries that have access to detailed plant-level data on the carbonate raw materials. Emissions data collected at the plant level should then be aggregated for purposes of reporting national emissions estimates. It is recognized that frequent calculations of emissions based on direct analysis of carbonates could be burdensome for some plants. As long as detailed chemical analyses of the carbonate inputs are carried out with sufficient frequency to establish a good correlation between the carbonates consumed at the plant level and the resulting alumina production, the sinter output may then be used as a proxy for carbonates for emissions calculations in the intervening periods. That is, a plant may derive a rigorously-constrained emission factor for the plant's alumina, based on periodic calibration to the carbonate inputs and outputs.

EQUATION 4.27B**TIER 2 AND 3: EMISSIONS BASED ON CARBONATE RAW MATERIAL INPUTS TO THE SINTERING KILN**

$$CO_2 \text{ Emissions} = \sum_i (M_{oi} \cdot C_{iCO_2}) + E_{LC} + EF_s \cdot M_s + (0.71 C_{Na_2O} \cdot V_s) / 1000 - E_{sp} - 44/12 \cdot (M_{rm} - E_{SKD} - E_{nf})$$

Where:

$CO_2 \text{ Emissions}$ = total emissions of CO₂ from sintering kiln, tonnes

$\sum_i (M_{oi} \cdot C_{iCO_2})$ = CO₂ emissions from carbonates in bauxite or nepheline ore decomposed in kiln, tonnes

M_{oi} = weight or mass of i ore recalculated per dry conditions consumed in the kiln, tonnes

C_{iCO_2} = the weighted average content of CO₂ 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 CO₂ in nephelines is determined as the difference in loss on ignition and SO₃), %

E_{LC} = CO₂ emissions released from lime calcination, t CO₂ / year. The calculation shall be done in accordance to Tier 2 or 3 approaches described in Volume 3 (Industrial Processes and Product Use), Chapter 2, Section 2.3.

$EF_s \cdot M_s$ = CO₂ emissions from soda carbonate decomposition, tonnes

EF_s = emission factor for soda carbonate forwarded to the kiln with ore tonnes CO₂ /tonnes soda carbonate (see Table 2.1 Chapter 2 Mineral Industry emissions)

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

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$(0.71 C_{Na2Ok} \bullet Vs) / 1000 = \text{CO}_2$ emissions from the decomposition of soda contained in a soda solution, tonnes

0.71 = stoichiometric conversion factor of CO_2 from Na_2O . Na_2O is measure in the soda solution.

C_{Na2O} = the content of sodium oxide (carbonate) in the soda solution, forwarded to the kiln, grams/litter

V_s = volume of soda solution, m^3

E_{sp} = CO_2 emissions captured during carbonization process and contained in produced Sodium carbonate, tonnes CO_2

$44/12 \bullet M_{rm}$ = CO_2 emissions based on the mass of carbon in bauxite or nepheline residue, tonnes

M_{rm} = Mass of carbon in bauxite or nepheline residue, tonnes

E_{SKD} = CO_2 emissions from un-calcined SKD not recycled to the kiln, tonnes.

E_{nf} = CO_2 emissions from carbon-bearing non-fuel materials, tonnes.

EQUATION 4.27C**EMISSIONS CAPTURED DURING CARBONIZATION PROCESS AND CONTAINED IN PRODUCED SODIUM CARBONATE**

$$E_{sp} = EF_s \bullet M_s$$

Where:

E_{sp} = CO_2 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_2 / tonnes soda carbonate (see Table 2.1 Chapter 2 Mineral Industry emissions).

M_s = weight or mass of soda produced for using out of plant, tonnes.

EQUATION 4.27D**EMISSIONS FROM UN-CALCINED SKD NOT RECYCLED TO THE KILN**

$$E_{SKD} = (M_{dr} + M_{dnr}) \bullet (100 \% / Eac) - M_{dr}) \bullet C_{CO2}$$

Where:

E_{SKD} = CO_2 emissions from un-calcined SKD not recycled to the kiln, tonnes.

M_{dr} = weight or mass of SKD recycled to the kiln, tonnes.

M_{dnr} = weight or mass of SKD not recycled to the kiln (= 'lost' SKD), tonnes.

Eac = efficiency of exhausted gases cleaning facilities at sintering kilns, percentage.

C_{CO2} = carbon content in dust recalculated in CO_2 , percentage.

EQUATION 4.27E**WEIGHTED AVERAGE CONTENT CO_2 IN 'I' BAUXITES (NEPHELINES)**

$$C_{iCO2} = \sum_i EF_i \bullet M_i \bullet F_i$$

Where:

C_{iCO2} = the weighted average content of CO_2 in i bauxites (nephelines) according to chemical analysis, assuming 100% calcination of the carbonate

EF_i = emission factor for the particular carbonate i , tonnes CO_2 /tonne carbonate (see Table 2.1 Chapter 2 Mineral Industry emissions)

M_i = weight or mass share of carbonate i consumed in the kiln, percentage

F_i = fraction calcination achieved for carbonate i , fraction¹, percentage

EQUATION 4.27F
WEIGHTED AVERAGE CONTENT OF CO₂ IN 'I' BAUXITES (NEPHELINES) RESIDUE

$$M_{rm} = M_{br} \cdot C_c$$

Where:

M_{rm} = Mass of carbon in bauxite or nepheline residue, tonnes

M_{br} = Mass of dry bauxite or nepheline residue disposed, tonnes

C_c = Weight or mass share of C in dry bauxite or nepheline residue, percentage

EQUATION 4.27G
EMISSIONS FROM CARBON-BEARING NON-FUEL MATERIALS

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

Where²:

E_{nf} = CO₂ emissions from carbon-bearing nonfuel materials, tonnes

M_k = weight or 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 CO₂/tonne carbonate

4.4.5.3 CHOICE OF EMISSION FACTORS FOR ALUMINA PRODUCTION

Emissions factors for lime production are in Volume 3, Section 3.3.1.2.

TIER 1 METHOD FOR SINTERING

It is impossible to define any universal default emissions factors because there are no national or industry average data related to bauxite processing by sintering processes. The implementation of sintering processes is determined by bauxite quality (Al₂O₃ content), carbonates and silica content in ore which can vary significantly. It is recommended that site specific data related to percentage of bauxite processed by sintering processes and, plant specific emissions factors for sintering, are used where possible - please refer to the Tier 2 and Tier 3 methods below.

TIER 2 METHOD FOR SINTERING

Data is not available to define worldwide, national or industry averages for content of CO₂ in bauxite. The CO₂ content in bauxite can vary significantly. If no carbonates specific data is available, it is *good practice* to define the total amount of carbonates or CO₂ and use this emissions factor for particular type of bauxite used in sintering. This can be determined as the difference in weight of ore before and after heating to temperatures when carbonates are decomposing with CO₂ emissions.

¹ For F_i , calcination fraction (Equation 4.33): 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_d 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 $F_d = 1.00$ will result in the correction for SKD to equal zero.

² The ignored CO₂ emissions from non-carbonate carbon (e.g., carbon in kerogen, carbon in fly ash) in the non-fuel raw materials can be (set $M_k \cdot X_k \cdot EF_k = 0$) if the heat contribution from kerogen or other carbon is < 5 percent of total heat (from fuels).

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Tier 2 approach to emissions factors for lime calcination is described in section 2.3.1.2 Choice of emission factors Chapter 2.

Weight or mass of soda forwarded to the kiln with ore should be site specific. If no data is available on soda purity, it is *good practice* to consider 100% purity soda is used in sintering. The Tier 2 approach for calculating emissions from soda contained in a soda solution should be based on site specific data.

The Tier 2 approach for carbonization is based on data for the amount of soda produced during the carbonization process and not used in sintering processes or other processes with carbonate decomposition on site. If no data on soda purity is available, it is *good practice* to consider 100% purity soda produced for external usage.

CO₂ emissions captured by other CO₂ 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:

- CO₂ in bauxite residue 0,1-2% of dry content,
- CO₂ in nepheline residue 0-2% of dry content.

Emissions correction factor for sintering kiln dust

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 an addition to the sintering emissions in the Tier 1 and 2 calculations, and 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 CO₂ generated in these source categories.

TIER 3 METHOD FOR SINTERING

The Tier 3 emission factors are based on the actual CO₂ contents of the carbonates present (see Equation 4.31 and Table 2.1) of Chapter 2. The Tier 3 approach requires the full accounting of carbonates (species and sources).

4.4.5.4 CHOICE OF ACTIVITY DATA

TIER 1 METHOD

In Tier 1, national-level (or where available, plant-level), data should be collected only for those plants where lime calcination processes are part of alumina production process (and where calcined lime is not obtained from other producers).

If a proportion of calcined lime is produced for uses other than alumina production, to avoid double counting CO₂ 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. CO₂ 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. Chapter 2.

If alumina plants have sintering processes, site specific data should be obtained related volume of alumina production, % of alumina produced with sintering and the respective emission factor for 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 as 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 plant has had significant change in technology of

sintering, a new emissions factor should be defined. In the cases where no such changes have taken place, the emissions factor should be update once every 10 years. Plant specific volume of alumina production, % of alumina produced with sintering and information about no changing in bauxite source or technology should be provided for each national-level GHG emissions calculation campaign.

TIER 2 AND 3 METHODS

For lime production process refer to Section 2.3.1.3 choice of activity data Chapter 2.

The Tier 2 method requires collection of sintering process data based on mass balance. It is suggested that if national surveys currently canvass alumina production data, the inventory compiler should investigate the possibility of expanding them to collect sintering process data. It is *good practice* to collect sintering process data directly from national statistics (if it such information are collected) or, preferably, from individual plants. It is also suggested that inventory compilers collect information on the carbon content of all input and output materials or flows. If possible, data should be collected to document SKD collection and recycling practices at the plants. 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 plant level conditions.

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 (which is typically calculated daily). Subsequently, the sintering production data may then be used as a proxy 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 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 percent of total carbonate) the plant can apply a constant value for the minor source(s) in intervening years before the next full investigation. Recognizing that estimating activity data for these smaller sources may lead to analytical (and other) errors, it may be assumed for emission calculation purposes that the minor source of carbonate is CaCO_3 , but this assumption should be transparently documented.

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

4.4.5.5 COMPLETENESS

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

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

In countries where only a subset of plants with lime production and bauxites/nephelines sintering processes report data for the Tier 3 method or where there is a transition from Tier 2 to Tier 3, it may not be possible to report emissions using a Tier 3 for all facilities during the transition. Where data on the carbonate inputs are not available for all plants to report using Tier 3, it may be possible to determine the share of production represented by non-reporting plants and use this information to estimate the remaining emissions using Tier 2 in order to ensure completeness during the transition period. A similar approach could be undertaken as a country moves from Tier 1 to Tier 2.

The potential for double counting also should be considered. For example, inventory compilers should review statistics used to estimate emissions from the source category 'Other Process Uses of Carbonates' and 'Lime production' to ensure that emissions reported in that source category do not result from the use of these carbonates in alumina production. Where carbonates are used for alumina production, the emission should be reported under Alumina Production. Finally, inventory compilers should include only process-related emissions from alumina

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production in this source category. To avoid double-counting, it is *good practice* to account for combustion-related emissions in the Energy volume.

There is one additional issue that, while not included in the current methodology, may become relevant for consideration in the future. Sodium alkaline contained in bauxite/nepheline residue area can re-absorb atmospheric CO₂. However, the rate of carbonation is very slow (years to centuries).

4.4.5.6 DEVELOPING A CONSISTENT TIME SERIES

For lime production refer to Section 2.3.1.5 Developing a consistent time series at Chapter 2.

Ideally countries shall try to find site specific data for all inventories years. But there are a lot of situations where there is no data especially for previous years in case of plant closing or significant changing of technology or sources of bauxites/nephelines. In that case inventory compiler shall attract industry experts to decide how to assess emissions in such cases based on extrapolation of CO₂ emission level figures with normalizing of them by volume alumina production, or based on applying of data from similar plants in the reporting country or average worldwide figures for similar technology.

Where data are not available, inventory compilers moving from a Tier 1 to a Tier 2 and from Tier 2 to Tier 3 approach may assume that there has not been a significant shift in the country from use of one carbonate input to another for Sintering. This is likely a reasonable assumption, specifically since limestone typically is the predominant carbonate input.

4.4.6 Uncertainty assessment for alumina production

Uncertainty estimates for lime production is described at Section 2.3.2. Uncertainty assessment. Chapter 2

Uncertainty estimates for Sintering process result predominantly from uncertainties associated with activity data, and to a lesser extent from uncertainty related to the emission factor.

4.4.6.1 EMISSION FACTOR UNCERTAINTIES

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

Under Tier 2, the major source of uncertainty is associated with determining the carbonates content of input materials to the sintering kiln. If carbonates containing data in input materials are available, the uncertainty of the emission factor is equal to the uncertainty of the CaO fraction and the assumption that it was all derived from CaCO₃ (Table 2.3). For Tier 3, there is relatively little uncertainty associated with the emission factors of the source carbonates because they are based on stoichiometric ratios. There may be some uncertainty associated with assuming, in Tier 3, that there is 100 percent calcination of carbonates in the SKD. In general, SKD is the least characterised factor for estimating CO₂ emissions from bauxite/nepheline sintering process, regardless of the Tier implemented.

4.4.6.2 ACTIVITY DATA UNCERTAINTIES

The uncertainty for percentage of bauxite/nepheline processing at sintering process is not so high. The level of uncertainty is indicated in the Table. 4.16B. The uncertainty in data on alumina production tonnages is about 1 percent.

For Tier 2, the uncertainty in data on weight or mass of *i* ore recalculated per dry conditions consumed in the kiln tonnages, is about 1-2 percent. Collecting data from individual producers (if complete) rather than using national totals will reduce the uncertainty of the estimate because these data will account for variations in conditions at the plant level. Except for SKD the greatest sources of uncertainty associated with Tier 3 are the uncertainties associated with identification of carbonate species (1-5 percent) and the weight of raw materials.

Although emissions are much smaller than from carbonates, there may be considerable uncertainty associated with estimating emissions from SKD in Tier 2 estimates, and also 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 attempt has been made to estimate the approximate uncertainties for different factors in Equations 4.27A-4.27G. The uncertainties are presented in Table 4.16B 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 4.16B should be combined.

TABLE 4.16B DEFAULT UNCERTAINTY VALUES FOR BAUXITE/NEPHELINE SINTERING PROCESS		
Uncertainty ^a	Comment	Tier
Chemical Analysis / Composition		
1-3%	Percentage of bauxite processing at sintering process	1
10%	Estimation of percentage of bauxite processing at sintering process	1
5%	Emission factor for sintering	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	2, 3
15%	Estimation of content of sodium oxide (carbonate) in the soda solution, forwarded to the kiln	2, 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	2
1%	Weight or mass share of particular carbonate consumed in the kiln	2, 3
2%	Fraction calcination achieved for carbonates	3
10%-20%	Assumption 100% of fraction calcination achieved for carbonate	2
3%	Weight or mass of organic or other carbon-bearing nonfuel raw material	2, 3
3%	Fraction of total organic or other carbon in specific nonfuel raw material	2, 3
50%	Estimation of weight or mass of organic or other carbon-bearing nonfuel raw material	2
50%	Estimation of fraction of total organic or other carbon in specific nonfuel raw material	2
1-3%	Kerogen (or other non-carbonate carbon) determination	3
Production Data		
1-2%	Reported (plant-level) alumina production data	1, 2, 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	2, 3
10%	Estimation of weight or mass of ore recalculated per dry conditions consumed in the kiln	2, 3
1-2%	Weight or mass of soda forwarded to the kiln with ore	2, 3
10%	Estimation of weight or mass of soda forwarded to the kiln with ore	2, 3
2%	Volume of soda solution	2, 3
35%	Estimation of volume of soda solution	2, 3
1-2%	Weight or mass of soda produced for using out of plant	2, 3
5%	CO ₂ emissions captured by other CO ₂ capturing technologies	2, 3
15%	Estimation of CO ₂ emissions captured by other CO ₂ capturing technologies	2, 3
5%	Mass of bauxite/nepheline residue disposed	
10%	Estimation of bauxite/nepheline residue disposed	

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TABLE 4.16B (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	2
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	2
1-2%	Efficiency of exhausted gases cleaning facilities at sintering kilns	3
10%	Estimation of efficiency of exhausted gases cleaning facilities at sintering kilns	2
1-2%	Carbon content in dust recalculated in CO ₂	3
10%	Estimation of carbon content in dust recalculated in CO ₂	2
^a Estimates are based on expert judgement.		

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

4.4.7.1 QUALITY ASSURANCE / QUALITY CONTROL (QA/QC)

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

COMPARISON OF EMISSIONS ESTIMATES USING DIFFERENT APPROACHES

Comparisons could be made between emissions estimated using different tiers. For example, if a bottom-up approach is used to collect activity data (i.e., collection of plant-specific data), then inventory compilers should compare the emissions estimates to the estimates calculated using national production data alumina production (top-down approach). In cases where a hybrid Tier 1/2 or Tier 2/3 approach is used during a transition period, it is considered *good practice* also to estimate emissions for all facilities using the lower Tier in order to compare the results of the analysis to the results derived using the hybrid approach. The results of such comparisons should be recorded for internal documentation, including explanations for any discrepancies.

REVIEW OF EMISSION FACTORS

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

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

SITE-SPECIFIC ACTIVITY DATA CHECK

For site-specific data, inventory compilers should review inconsistencies between sites to establish whether they reflect errors, different measurement techniques, or result from real differences in emissions, operational

conditions or technology. For alumina production, inventory compilers should compare plant data with other plants in the country.

Inventory compilers should ensure that emission factors and activity data are developed in accordance with internationally recognised and proven measurement methods. If the measurement practices fail this criterion, then the use of these emissions or activity data should be carefully evaluated, uncertainty estimates reconsidered and qualifications documented. If there is a high standard of measurement and QA/QC in place at most sites, then the uncertainty of the emissions estimates may be revised downwards.

4.4.7.2 REPORTING AND DOCUMENTATION

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates. Specific documentation and reporting relevant to this source category follow.

TIER 1 METHOD

Any information regarding the carbonates content of sintering feed should be documented, including use of default values different from those discussed in section 4.4.3.2.

TIER 2 METHOD

Tier 2 documentation should include a description of how sintering input and output and was estimated by the reporting entity (i.e., directly weighed, weight determined by volume, calculated from raw material inputs, etc.) and at what level the activity data were collected (i.e., plant level or national level). The method (e.g., country specific or IPCC default) for determining the carbonates content of sintering feed should be documented along with any plant-specific information regarding the quantity and type of non-carbonate feeds to the kiln. All procedures used to quantify and determine the degree of calcination of SKD should be documented. Where the assumption that emissions of SKD are equal to 2 percent of emissions from sintering process is made, this should be transparently reported.

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 CO₂ calculations. Instead, a full investigation will 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.

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1870 **4.6 LEAD PRODUCTION**

1871 No Refinement

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1874 **4.7 ZINC PRODUCTION**

1875 No Refinement

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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 alloys¹, 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, yttrium and the lanthanides. 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 predominantly carried out using a molten fluoride-salt electrolytic reduction process that is similar to primary aluminium’s Hall-Heroult process² (refer to Chapter 4.4) and consists of (Vogel & Friedrich 2015; Zhang *et al.* 2017; Vogel & Friedrich 2018) :

- Dissolving and electrolytically reducing REOs (e.g. Nd₂O₃) in a molten salt of rare earth fluorides (REF₃) and lithium fluoride (LiF) – an example composition is 85%wt NdF₃, 10% LiF and 5% Nd₂O₃ for Nd metal production;
- Carbon anodes, 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 the most commonly produced RE metal by this process; other RE metals and alloys produced by the same process include Pr, Nd-Pr, Dy-Fe, La, Ce 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 can be categorised into technology classes by electrical current (and hence size), the configuration of anodes and cathodes and the level of automation in the process, as follows:

- *LA* – Low Amperage (<10 kA);
- *HA* – High Amperage (≥10 kA);
- *HAA* – High Amperage (≥10 kA) *with* Automatic Process Control.

Low amperage technologies (LA) typically employ small round-shaped cells, with only single (or several) vertical anodes and cathodes and typically have very low levels of automation. *High amperage technologies* (HA and HAA) typically are larger, round 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). Some high amperage technologies may be equipped with ‘*Automatic Process Control*’ (HAA), defined as having one or more of the following:

- Automatic rare earth oxide feeding
- Continuous metal production that is not interrupted for anode changes and metal removal

¹ Carbon dioxide (CO₂) emissions associated with the production of electricity from fossil fuel combustion to produce rare earth metals and alloys are covered in Volume 2: Energy.

² Due to the many 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 CO₂ 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.

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- 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.* 2016):

- Carbon dioxide (CO₂) emissions from the consumption of carbon anodes in the electrolytic reaction converting rare earth oxides to rare earth metals;
- Perfluorocarbons (PFCs) emissions of CF₄ and C₂F₆ during anode effects.

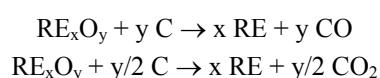
Carbon monoxide (CO) is another major process emission; SO₂ might also be emitted in very small amounts.

The decision trees in Figure 4.17 and Figure 4.18 provide guidance for selecting a methodology estimating CO₂ 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.

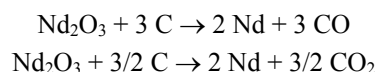
4.8.2 Methodological Issues

4.8.2.1 CHOICE OF METHOD FOR CO₂ EMISSIONS FROM PRIMARY RARE EARTH METAL PRODUCTION

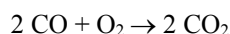
During normal operations, rare earth metals are produced at the cathode and carbon is consumed at the anode, forming carbon monoxide (CO) and carbon dioxide (CO₂) gases by electrolysis, as per the generic electrolytic reduction reactions below for production of any rare earth metal (RE) from its oxide (REO) (Liu *et al.* 2001; Vogel *et al.* 2016) :



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.* 2016), it is assumed that all CO gas oxidises in the process and is ultimately emitted to the atmosphere as CO₂ gas (Vogel & Friedrich 2018), as follows:



Most CO₂ emissions therefore result from the electrolysis reaction of the carbon anode with rare earth oxides (REO). The consumption of carbon anodes¹ is the principal source of process related CO₂ emissions from primary rare earth production. The reactions leading to carbon dioxide 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.

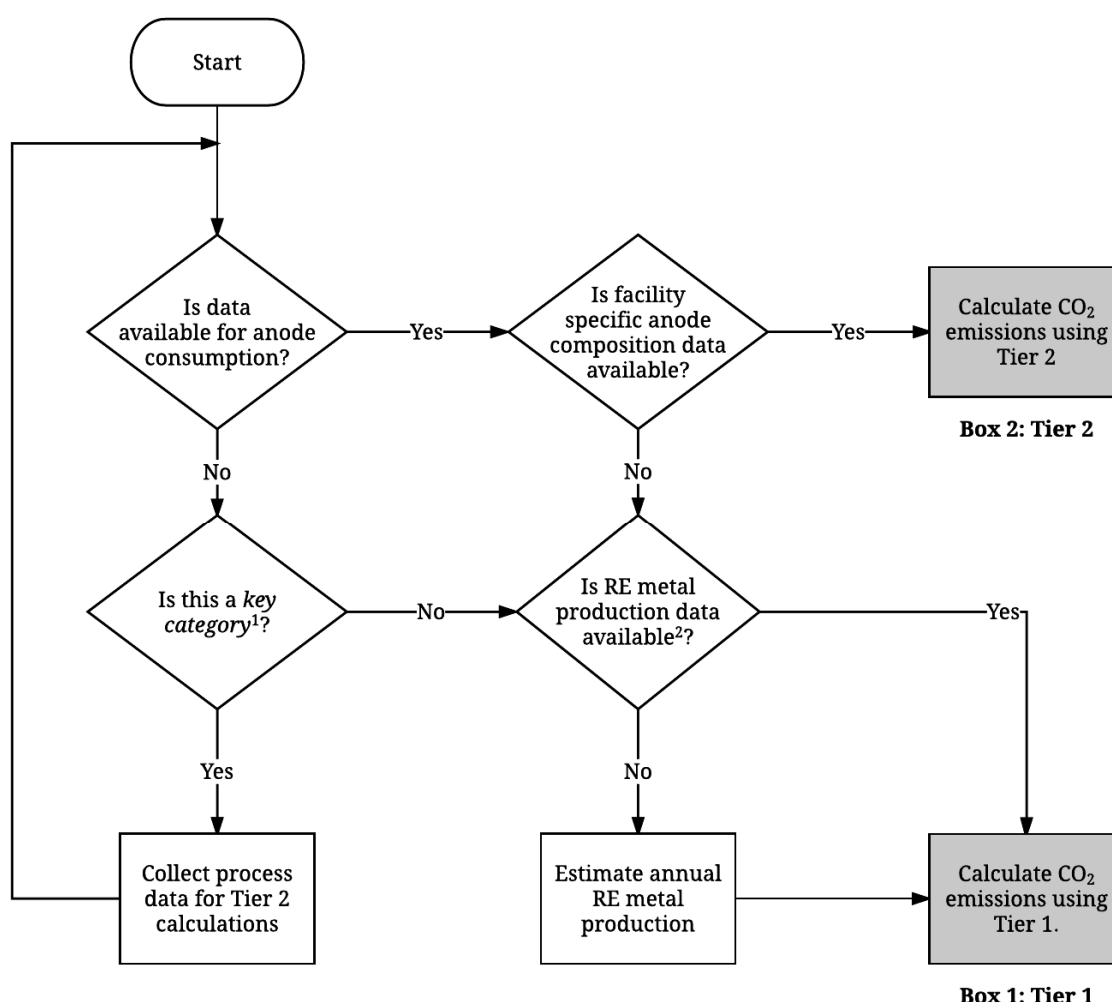
Due to a lack of published information, all other sources of process-related CO₂ emissions have not been considered in these guidelines. For example, it is assumed that industrial rare earth facilities currently do not

¹ 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.

manufacture or ‘pre-bake’ their own carbon anodes (due to low process volumes compared to the primary aluminium industry, refer to section 4.4) and hence GHGs from anode baking are not considered here.

The decision tree shown in Figure 4.17 describes good practice in choosing the CO₂ inventory methodology appropriate for national circumstances.

Figure 4.17 Decision tree for calculation of CO₂ 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 CO₂ 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 currently only provides 2 tiers, one using metal-production estimates and a second using facility-specific anode consumption + anode composition data. An additional Tier 2 method using default anode composition data (corresponding to the CO₂ decision tree for aluminium production, sub-chapter 4.4) has not been provided for this First Order Draft (FOD), since there is no published default anode composition data for rare earths available. If this data does become available from industrial sampling campaigns for three RE facilities currently underway in China, an additional Tier 2 method using default anode composition factors will be proposed in the Second Order Draft (SOD).

Tier 1 method for CO₂ emissions – default emission factors

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The Tier 1 method for calculating CO₂ emissions uses a lower order estimate based only on rare earths metal production. Given the uncertainty associated with the Tier 1 method, it is good practice to use higher tier methods if CO₂ from primary rare earths is a key category.

Total CO₂ emissions from all rare earth (RE) metals and alloys produced are calculated according to Equation 4.35.

EQUATION 4.35
PROCESS CO₂ EMISSIONS FROM ANODE CONSUMPTION (TIER1 METHOD)

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

Where:

E_{CO_2} = Total CO₂ emissions from carbon anode consumption (tonnes CO₂)

EF_i = Specific emission factor for RE metal/alloy type i (tonnes CO₂/tonne RE metal)

Note that while Equation 4.35 enables calculation of CO₂ emissions by each RE metal/alloy produced (assuming production data for each metal and alloy type i is available), the lack of published data means that than individual default emission factors are not available for all RE metal or alloy types¹. Only one default Tier 1 emission factor for a generic RE metal has been provided in these guidelines (refer to Section 4.8.2.2). Therefore, it is acceptable to use Equation 4.35 with total RE metal production data, without differentiation into RE metal and alloy types.

Tier 2 method for CO₂ emissions – by facility-specific carbon mass balance

[*Note that a Tier 2 method for CO₂ accounting using actual anode consumption + default anode composition values (corresponding to Tier 2 methods for CO₂ for the aluminium industry, sub-chapter 4.4) has not been provided, since default anode impurity values are not currently available; however if they do become available by the Second Order Draft (SOD), an additional Tier 2 method using default anode composition factors will be added, and the Tier 2 method below using anode consumption + actual composition factors will become Tier 3].

In the Tier 2 method, CO₂ emissions are calculated using a mass balance approach that assumes that the carbon content of net anode consumption² is all ultimately emitted to the atmosphere as CO₂ gas³. The Tier 2 methods 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 2 method will depend on whether process data for (i) net carbon anode consumption and (ii) baked anode composition are both available from individual facilities.

CO₂ emissions for the Tier 2 method are calculated according to Equation 4.36. This requires facility-specific operating data for all the components in Equation 4.36 (note that an assumption is that the same anode composition is used for production of all RE metals and alloys).

EQUATION 4.36
PROCESS CO₂ EMISSIONS FROM ANODE CONSUMPTION (TIER2 METHOD)

$$E_{CO_2} = \sum_i (NAC_i \cdot MP_i) \cdot \frac{100 - S_a - Ash_a}{100} \cdot \frac{44}{12}$$

Where:

E_{CO_2} = Total CO₂ emissions from carbon anode consumption (tonnes CO₂)

¹ 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.

² ‘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.

³ While CO is the most dominant gas product from the rare earths electrolytic reduction reaction [Liu 2001], it is assumed that any CO formed eventually is converted to CO₂ gas (as is assumed for the primary aluminium industry, in Section 4.4).

2022	MP_i =	Total metal production for RE metal/alloy type i (tonnes RE metal)
2023	NAC_i =	Net anode consumption per tonne of RE metal/alloy type i (tonnes/tonne RE metal)
2024	S_a =	Sulfur content in baked carbon anodes (wt %)
2025	Ash_a =	Ash content in baked carbon anodes (wt %)
2026	44/12 =	CO ₂ molecular mass: carbon atomic mass ratio (dimensionless)

2027

2028 Equation 4.36 should be applied to each rare earth smelter in the country and the results summed to arrive at total
 2029 national emissions. It is possible to use a hybrid Tier 1/2 or 3 approach if facility specific net anode consumption
 2030 and composition data (ash or sulfur content) are not available for each smelter.

2031 4.8.2.2 CHOICE OF EMISSION FACTORS FOR CO₂ EMISSIONS FROM 2032 PRIMARY RARE EARTH METAL PRODUCTION

2033 Tier 1 method for CO₂ emissions

2034 Table 4.26 lists the default emission factors for CO₂ per tonne of RE metal, for use in Equation 4.35. Given the
 2035 lack of published data and since only minor differences in emission factors (< ±10%) are expected across different
 2036 RE metals and alloy types¹, only one default emission factor is provided for a generic RE metal. This uses Nd
 2037 metal production as the basis, since it is the most commonly produced RE metal via the fluoride-salt electrolysis
 2038 process.

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TABLE 4.26 TIER 1 TECHNOLOGY SPECIFIC EMISSION FACTORS FOR CALCULATING CO ₂ EMISSIONS FROM ANODE CONSUMPTION (REFER TO EQUATION 4.35)		
Rare Earth Metal / Alloy i	Emission Factor, EF_i (tonnes CO ₂ /tonne RE metal)	Uncertainty (±%)
Nd metal, and all other Rare Earth metals/alloys	0.65 [#] *TBC	±95% *TBC

2040 Source:

2041 [#] The default emission factor for a generic RE metal is based on a first principles calculation, taking electrolysis of Nd₂O₃ to Nd metal as a
 2042 basis (see Section 4.8.2.1 for stoichiometric reactions), assuming a CO/CO₂ gas production ratio of 3:1 (75% CO and 25% CO₂) by direct
 2043 electrolysis at 1050°C and anode current density of 1.0 A/cm² (Liu *et al.* 2001; Vogel & Friedrich 2015). Total CO₂ emitted is then
 2044 calculated assuming: (i) all CO is ultimately oxidised to CO₂, (ii) process has a 70% faradaic current efficiency (% anode carbon that is
 2045 electrolytically consumed to produce metal), and (iii) an additional 20% anode carbon consumed via non-electrolytic processes (oxidation of
 2046 carbon due to exposure with air). Using the same first principles method, the obtained net anode carbon consumption (180 kg carbon / tonne
 2047 RE metal) is similar to figures obtained from ongoing industrial surveys of rare earth facilities (see *TBC note below). The ±95% uncertainty
 2048 is provided given lack of published industrial information to support the default emission factor.

2049 *TBC = To be confirmed. Tier 1 default emission factors and uncertainties for CO₂ will be determined from either existing published
 2050 literature, and/or from the industrial sampling campaigns for three RE facilities currently underway in China. We hope to provide these for
 2051 the Second Order Draft (SOD) of these guidelines. An default emission factor above is estimated above based on first principles, calculations
 2052 can be provided to Expert Reviewers on request.

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2054 Tier 2 methods for CO₂ emissions

2055 The most significant factors in Equation 4.36 are metal production and net anode consumption for each RE metal
 2056 or alloy type i . Both these parameters should be collected from individual operating facilities for use with Tier 2.
 2057 The other compositional terms in the equation make minor adjustments for non-carbon components of the anodes
 2058 (e.g. sulphur and ash) and thus are not as critical. Tier 2 is based on the use of specific operating facility data for
 2059 these minor components. Carbon consumed per tonne of metal produced is typically recorded by primary rare
 2060 earth production facilities given its economic significance; facilities can refer to this as 'net anode or net carbon
 2061 consumption.

¹ Using Nd metal as a base case, the impact of calculating similar CO₂ emission factors (per tonne RE metal) for other 'light' rare earth metals is only +4% / -8% for production of La to Gd metal, due to the similarities in atomic mass for these rare earth metals. Note that this assumes the same conditions as applied for Nd metal, i.e. CO/CO₂ ratio, temperature, anode current density, current efficiency and 'airburn' (carbon oxidation by exposure to air).

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TABLE 4.27 DATA SOURCES AND UNCERTAINTIES FOR PARAMETERS USED IN TIER 2 METHOD FOR CO₂ EMISSIONS FROM ANODE CONSUMPTION (REFER TO EQUATION 4.36)		
Parameter	Data Source	Uncertainty (±%)
<i>MP_i</i> : total metal production for RE metal type <i>i</i> (tonnes metal per year)	Individual facility records	±10% ^a (*TBC)
<i>NAC_i</i> : net anode consumption per tonne of RE metal type <i>i</i> (tonnes per tonne metal)	Individual facility records	±10% ^b (*TBC)
<i>S_a</i> : sulphur content in baked anodes (wt %)	Individual facility records	±10% ^b (*TBC)
<i>Ash_a</i> : ash content in baked anodes (wt %)	Individual facility records	±10% ^b (*TBC)

2063

Source:

2064

^a 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.

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^b Uncertainties for CO₂ 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 (section 4.4, Table 4.11 in the 2006 IPCC Guidelines, uncertainties for Tier 3 method for CO₂ emissions from prebake cells).

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*TBC = To be confirmed. These will be refined from either new published literature, and/or from the industrial sampling campaigns and surveys for rare earth facilities in China. The Lead Authors of these guidelines hope to provide these for the Second Order Draft (SOD).

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4.8.2.3 CHOICE OF METHOD FOR PFCs

During electrolysis of a RE metal, rare earth oxides (REOs) are dissolved in a fluoride melt comprising of rare earth fluorides (RE_xF_y) and lithium fluoride (LiF). An example melt composition for Nd metal production is 85% wt NdF_3 , 10% LiF and 5% Nd_2O_3 .

Perfluorocarbons (CF_4 and C_2F_6 , collectively referred to as PFCs) are formed from the reaction of the carbon anode with the fluoride melt (e.g. NdF_3 or DyF_3) during a process upset condition known as an ‘anode effect’. This occurs when the concentration of dissolved REO in the electrolyte is too low to completely support the standard anode reaction (normally producing RE metal and CO/CO_2 gases), enabling additional anode reactions that form PFC gases (Vogel *et al.* 2016; Zhang *et al.* 2017).

Box 4.4

ANODE EFFECT DESCRIPTION (FOR RARE EARTH METAL PRODUCTION BY FLUORIDE ELECTROLYSIS)

An anode effect is a process upset condition where an insufficient amount of rare earth oxide is dissolved in the electrolyte, resulting in the emission of PFC-containing gases. 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.

When generation of PFC-containing gases is associated with elevated voltage [**TBC*], it is termed a ‘*high voltage anode effect*’ (*HVAE*). On the other hand, when PFC generation occurs without elevated voltage, it is termed a ‘*low voltage anode effect*’ (*LVAE*).

**TBC*: To confirm if any particular voltages currently used in rare earth smelters, e.g. aluminium smelting’s 8V triggers.

In choosing a method for PFC emissions, it should be noted that the uncertainty associated with the Tier 2 methodology is significantly lower than for Tier 1; therefore Tier 2 is strongly recommended if this is a *key category*. However, the Tier 2 method requires obtaining facility-specific emission factors; these are to rare earth industry are currently unavailable, the US EPA and IAI protocols for measurement of PFCs in the aluminium smelting industry (International Aluminium Institute 2006; US Environmental Protection Agency & International Aluminium Institute 2008) provide good analogous references. Note however that unlike the aluminium industry, the Tier 2 methodology for rare earths estimates PFCs using production-based emission factors only; the method does not consider more detailed process data (e.g. coefficients and performance data for anode effects as per the aluminium industry, refer to section 4.2.2.3) due to a lack of published data to support it.

The decision tree in Figure 4.18 describes *good practice* in choosing the PFC inventory methodology appropriate for national circumstances. The Tier 2 approach is preferred because plant-specific emission factors will lead to estimates that are more accurate. If no PFC measurements have been made to establish Tier 2 plant-specific emission factors, the Tier 1 method can be used until measurements have been made. Countries can use a combination of Tier 1 and Tier 2 depending on the type of data available from individual facilities.

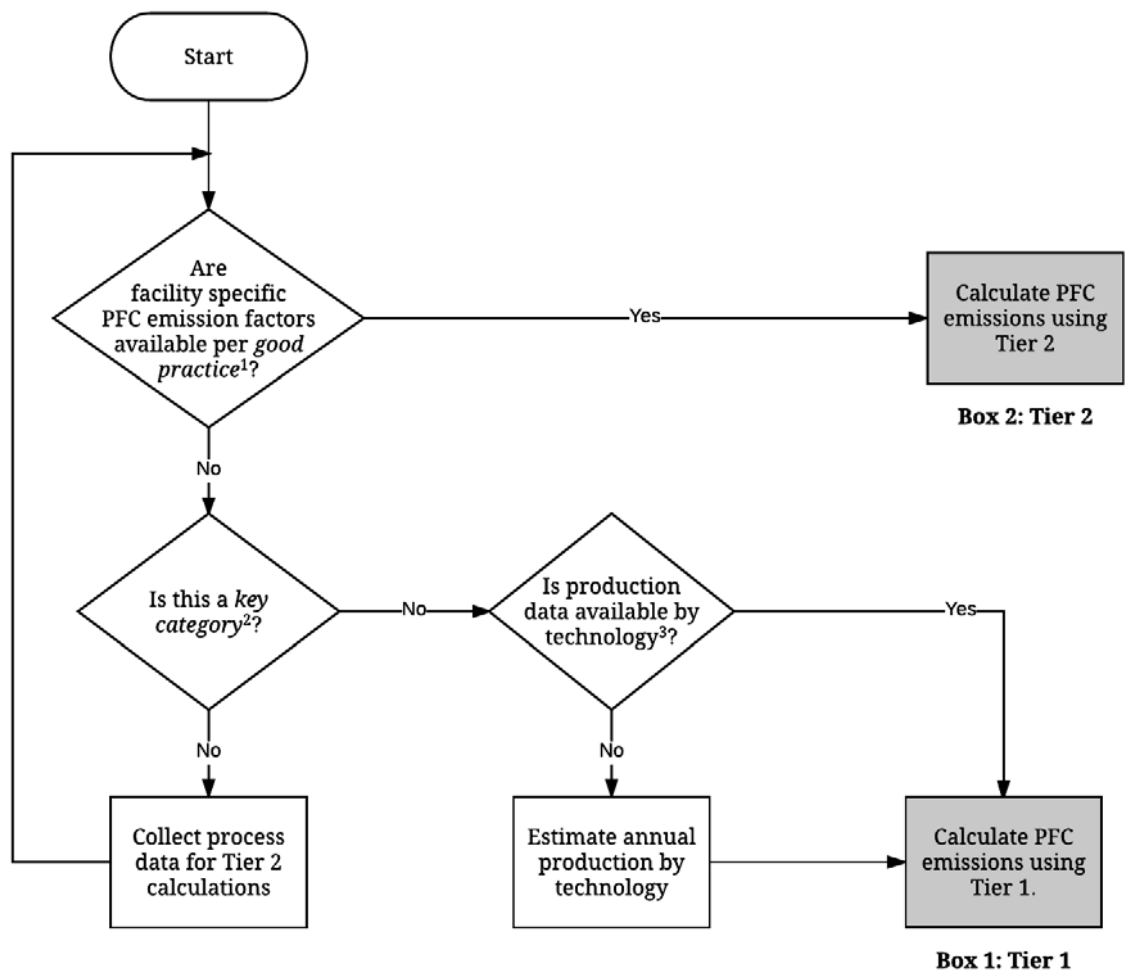
Note that while the fundamentals mechanisms that generate PFCs and anode effects in the rare earths industry are similar to those in primary aluminium production (refer to *2006 IPCC Guidelines*, Volume 3, Chapter 4, sub-chapter 4.4), the current lack of automation typically found in the rare earths industry prevents the use of anode effect performance statistics from the process as a more accurate methodology for estimating PFCs (as per Tier 2 and 3 methods for PFC accounting in primary aluminium production, which uses ‘anode effect minutes per cell per day’ as activity data). Therefore, higher tier methods using process performance statistics or activity data have not been included in these guidelines¹.

be calculated from measurement data obtained using good measurement practices. While guidelines specific to the

¹ Accounting of PFCs using 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 may not be reflective of the current state of the rare earths industry.

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Figure 4.18 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 unavailable, 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 by technology; this should be either obtained or estimated.

Tier 1 and Tier 2 method for PFCs – by production and technology type

Both Tier 1 and Tier 2 methods for calculating PFCs employ emission factors that are based on metal production.

The Tier 1 method uses default emission factors, differentiated for the three production technology types (LA, HA and HAA). PFC emissions can be calculated according to Equation 4.37, where emission factors for CF₄ and C₂F₆ gases are both default emission factors (refer to Table 4.28). The level of uncertainty in the Tier 1 methodology is greater because individual facility emissions performance¹ are not taken into account.

Note that default emission factors are not available for the HAA technology class, due to the scarcity of data. It is recommended that Tier 2 be used to estimate PFCs for facilities with HAA technology, provided facility-specific emission factors are available.

EQUATION 4.37
PFC EMISSIONS FROM ANODE CONSUMPTION (TIER1 AND TIER2 METHODS)

$$E_{CF_4} = \sum_{i,j} (EF_{CF_4, ij} \cdot MP_{ij})$$

and

$$E_{C_2F_6} = \sum_{i,j} (EF_{C_2F_6, ij} \cdot MP_{ij})$$

Where:

E_{CF_4} = Emissions of CF₄ from RE metal production, kg CF₄

$E_{C_2F_6}$ = Emissions of C₂F₆ from RE metal production, kg C₂F₆

$EF_{CF_4, ij}$ = Emission factor by RE metal *i* and technology *j* for CF₄, kg CF₄/tonne RE metal

$EF_{C_2F_6, ij}$ = Emission factor by RE metal *i* and technology *j* for C₂F₆, kg C₂F₆/tonne RE metal

MP_{ij} = Metal production by RE metal *i* and technology *j*, tonnes RE metal

The Tier 2 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 and are obtained using established measurement practices and protocols (refer to analogues guidelines for the aluminium industry in (International Aluminium Institute 2006; US Environmental Protection Agency & International Aluminium Institute 2008)). If facilities are equipped with multiple technology types (LA, HA and HAA), it is recommended that emission factors be obtained for each technology class. It is recommended that Tier 2 be used when PFCs from rare earths is a *key category*, provided facility-specific emission factors are available.

Note that while Equation 4.37 enables calculation of PFC emissions by individual RE metals and alloys produced (e.g. for Nd, Pr, La, Ce, Nd-Pr, Dy-Fe, mischmetal, etc), default emission factors are not available for each RE metals and alloys due to the scarcity of published industrial emissions data². As such, default Tier 1 emission factors are only provided for a generic rare earth metal, differentiated by technology type (refer to Section 4.8.2.4). Therefore, it is acceptable to use Equation 4.37 without differentiation of RE metal and alloys produced.

For Tier 2, 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 CF₄ and C₂F₆ emissions for each RE metal/alloy and technology type and total CF₄ and C₂F₆ 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.

¹ PFC emissions performance is impacted by 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 insufficient supporting data that characterises industrial emissions according to process performance statistics (e.g. anode effect performance).

² While Tier 1 default emission factors are not available for specific RE metals/alloys, Equation 4.35 has been provided as a template for the future (when such factors might become available) and for potential use in Tier 2 calculations.

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4.8.2.4 CHOICE OF EMISSION FACTORS FOR PFCs

Tier 1: Technology-based default emission factors for PFCs

Default emission factors for Tier 1 method are provided in Table 4.28. Note that default emission factors are not available for the HAA technology class, due to the scarcity of data. For facilities with HAA technology type production, it is recommended that Tier 2 be used to estimate PFCs, provided facility-specific emission factors are available; a final alternative would be to use Tier 1 default emission factors for the HA technology type.

TABLE 4.28 DEFAULT EMISSION FACTORS AND UNCERTAINTY RANGES FOR THE CALCULATION OF PFC EMISSIONS FROM RARE EARTH PRODUCTION BY TECHNOLOGY TYPE (TIER 1 METHOD, REFER TO EQUATION 4.37)				
Technology <i>j</i>	CF ₄		C ₂ F ₆	
	EF _{CF4} (kg/tonne metal)	Uncertainty (+/-%)	EF _{C2F6} (kg/tonne metal)	Uncertainty (+/-%)
LA – low amperage	10 ^a *TBD	+7257% / -99% ^a *TBD	1 ^b *TBD	+11500% / -99% *TBD
HA – high amperage	*TBD	*TBD	*TBD	*TBD
HAA – high amperage with automatic process control	NA ^c	NA ^c	NA ^c	NA ^c

Sources/Notes:

^a CF₄ default emission factor based on the average of three values: PFC measurements obtained for production of (i) Nd metal (16 cells) and (ii) Dy-Fe alloy (individual cell) in low amperage technology in China (Zhang *et al.* 2017) and (iii) modelled 'medium-emission' scenario for Nd metal (Vogel & Friedrich 2018) based on mass balance of NdF₃ inputs to replace lost fluorides. Uncertainties estimated based on a modelled 'worst-emission' scenario (Vogel & Friedrich 2018) for the higher bound of uncertainty and lowest measured industrial CF₄ emissions on 16 Nd cells in China (Zhang *et al.* 2017) for the lower bound of uncertainty.

^b C₂F₆ default emission factor based on application of CF₄/C₂F₆ ratios of 10:1 (measured in laboratory conditions for Nd metal (Vogel & Friedrich 2018)) on the CF₄ default emission factor. Uncertainties estimated based on a modelled 'worst-emission' scenario (Vogel & Friedrich 2018) for the higher bound of uncertainty and for the lower bound of uncertainty, no detected C₂F₆ was detected in industrial measurements of Nd metal and Dy-Fe alloy production cells in low amperage technology in China (Zhang *et al.* 2017).

^c NA = No default emission factors currently available; however, this technology class is expected to be significant in the future.

*TBD = to be determined. All highlighted Tier 1 default emission factors and uncertainties for PFCs will be determined from either existing published literature, and/or from the industrial sampling campaigns for three rare earth facilities currently underway in China for LA and HA technology types (HAA is not expected to be covered by this work, therefore no default emission factors are likely to be provided). We hope to provide these for the Second Order Draft (SOD) of these guidelines.

Tier 2: Facility-specific emission factors for PFCs

The Tier 2 facility-specific emission factors, determined through direct PFC measurements at individual facilities is listed in Table 4.29.

TABLE 4.29 DATA SOURCES AND UNCERTAINTIES FOR PARAMETERS USED IN TIER 2 METHOD FOR PFC EMISSIONS (REFER TO EQUATION 4.37)		
Parameter	Data Source	Uncertainty (+/-%)
EF_{CF4} : CF ₄ emission factor for metal type i and technology type j (kg CF ₄ /tonne RE metal)	Individual facility records	*TBD
EF_{C2F6} : C ₂ F ₆ emission factor for metal type i and technology type j (kg C ₂ F ₆ /tonne RE metal)	Individual facility records	*TBD
MP_i : metal production for RE metal type i and technology type j (tonnes metal per year)	Individual facility records	±10 ^a (*TBD)

Source:

^aUncertainties 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.

*TBD = To be determined / confirmed. These will be refined from either new published literature, and/or from the industrial sampling campaigns for rare earth facilities in China. We hope to provide these for the Second Order Draft (SOD).

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 CO₂ 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 2 facility-specific emission factors for individual facilities, where good measurements have been taken to establish facility-specific emission factors.

For CO₂ emissions, it is also *good practice* to collect data to support Tier 2 methods, which requires facility specific information on anode consumption and average anode composition to calculate CO₂ 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 (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 carbon dioxide 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 2 methods utilise metal production statistics to estimate emissions. Backcasting of Tier 2 methods is preferred over the use of Tier 1 emission factors. Because PFC emissions have only recently become a focus area of the rare

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earths industry, the majority of facilities are unlikely to have any further activity data to support any other methodologies based on process-data for PFC-generating anode effects (as per the primary aluminium industry).

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. Expert advice is also available from the [*TBC - Rare Earths Industry Association - to confirm whether a global or Chinese industry association exists with whom inventory compilers can interact with and obtain further guidance] regarding greenhouse gas emissions and typical industry emissions from aluminium production.

4.8.3 Uncertainty assessment

There are major differences in the uncertainty for PFC emissions depending on the choice of Tier 1 or Tier 2 methods. The differences in uncertainty resulting from the choice of Tier 1 or Tier 2 methods for CO₂ emissions is smaller, but still significant.

4.8.3.1 EMISSION FACTOR UNCERTAINTIES

Uncertainties in CO₂ emission factors

For CO₂ emissions, there are major differences in the uncertainty of emissions depending on the choice of Tier 1 or 2 methods. The uncertainty in emission factors for calculating CO₂ emissions from carbon anode consumption for Tier 2 should be less than $\pm 20\%$ (*TBC), and less than $\pm 95\%$ (*TBC) for Tier 1. While Tier 1 default emission factors are calculated using the same first principles as Tier 2 (mass-balance assuming all carbon content in the net anode consumed is emitted as CO₂), there are a number of assumed factors for Tier 1, each of which increases the level of uncertainty. Assumptions include (i): CO/CO₂ gas product ratio of 3:1 from the process, 70% (*TBC) current efficiency, anode composition of 100% graphite, 20% (*TBC) anode carbon oxidised due to exposure to air, and using Nd metal as the base scenario. Differences between Tier 1 and 2 methods are due to uncertainties from these assumptions. The use of facility-specific net anode consumption and anode compositional data in the Tier 2 method removes the need for these assumptions, leading to much lower uncertainty in calculating CO₂ using Tier 2. 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 CO₂ 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 2 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 one set (*TBC) of industrial PFC measurements from rare earth facilities (Zhang *et al.* 2017) 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, default emission factors are only available for LA and HA technology types. No default emission factors are available for the HAA technology (equipped with automatic process control); two alternative options are to (i) choose the Tier 2 method, if facility-specific emission factors are available (based on direct PFC measurements) or (ii) use the Tier 1 default emission factors for the HA technology. In order to achieve lower uncertainty Tier 2 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 2 coefficients will have an uncertainty of $\pm(\text{TBC})\%$ at the time coefficients are measured.

[*TBC – This section will need to be revised again following results from the industrial sampling campaigns for three rare earth facilities currently underway in China for LA and HA technology types (HAA is not expected to be covered by this work, therefore no default emission factors are likely to be provided). We hope to provide these revisions in time for the Second Order Draft (SOD) of these guidelines.]

4.8.3.2 ACTIVITY DATA UNCERTAINTIES

While there should be minor uncertainties in the data for annual production of RE metals (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 (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 CO₂ 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 4.27 and Table 4.28 for carbon dioxide specific emissions. Similarly, the facility PFC emission factors per tonne RE metal should be compared with those noted in Table 4.29. It is suggested that any inventory value outside the 95% 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. Until a rare earths industry-specific guideline or protocol has been established, the US EPA 'Protocol for Measurement of Tetrafluoromethane (CF₄) and Hexafluoroethane (C₂F₆) 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, due to the similarities between aluminium and rare earths fluoride-electrolysis processes¹. Inventory compilers should encourage plants to use this method for developing Tier 2 PFC emission factors. Significant differences between calculated coefficients based on PFC measurements and the industry average Tier 1 emission factors for similar RE technology 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 should not exceed $\pm 10\%$ 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 of up to $\pm 100\%$. 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.

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 CF₄ and C₂F₆ emissions are reported separately on a *mass basis*.

¹ Note that unlike the aluminium industry, the Tier 2 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 aluminium industry GHG protocols US Environmental Protection Agency & International Aluminium Institute. (2008) Protocol for Measurement of Tetrafluoromethane (CF₄) and Hexafluoroethane (C₂F₆) Emissions from Primary Aluminum Production. 42 pages. and section 4.2.2.3), due to a lack of published data to support it.

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2326 The supporting information necessary to ensure transparency in reported emissions estimates is shown in Table
 2327 4.30 below.

2328 Much of the production and process data are considered proprietary by operators, especially where there is only
 2329 one smelter in a country. It is *good practice* to exercise appropriate techniques, including aggregation of data, to
 2330 ensure protection of confidential data.

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TABLE 4.30 GOOD PRACTICE REPORTING INFORMATION FOR CALCULATING CO₂ AND PFC EMISSIONS FROM RARE EARTH METAL PRODUCTION BY TIER		
Data	Tier 2	Tier 1
CO₂ emissions		
Annual national production (by metal and alloy type)		X
Annual production by facility (by metal and alloy type)	X	
Net anode consumption	X	
Anode composition	X	
PFC emissions		
Annual national production (by LA, HA or HAA technology and metal/alloy type)		X
Annual production by facility (by LA, HA or HAA technology and metal/alloy type)	X	
Default technology emission coefficients		X
Facility-specific emission coefficients	X	
Supporting documentation	X	X

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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>

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.

European Monitoring and Evaluation Programme & European Environment Agency. (2016) Air pollutant emission inventory guidebook.

International Organization for Standardization. (2013) ISO 14404-1:2013. Calculation method of carbon dioxide emission intensity from iron and steel production - Part 1: Steel plant with blast furnace.

International Organization for Standardization. (2013) ISO 14404-2:2013. Calculation method of carbon dioxide emission intensity from iron and steel production - Part 2: Steel plant with electric arc furnace (EAF).

Joint Research Center. (2013) Best Available Techniques (BAT) Reference Document for Iron and Steel Production.

Office of Air and Radiation & U.S. Environmental Protection Agency. (2009) Technical support document for the iron and steel sector: proposed rule for mandatory reporting of Greenhouse.

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.

Sector Policies and Programs Division, Office of Air Quality Planning and Standards & U.S. Environmental Protection Agency. (2012) Available and Emerging Technologies for Reducing Greenhouse Gas, Emissions from the Iron and Steel Industry.

ThyssenKrupp Industrial Solutions. (2014) Coke plant technologies.

Zhang, X., Wu, G., Wu, S. & Xiang, X. (2012) Determination of carbon dioxide emission factors in typical processes for large iron-steel companies. *Acta Scientiae Circumstantiae* **42**(8): 2024-2027.

SECTION 4.4

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, 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, 2005.

U.S. EPA and IAI (2003), U.S. Environmental Protection Agency and International Aluminium Institute, USEPA/IAI Protocol for Measurement of PFCs from Primary Aluminium Production, EPA 43-R-03-006, May 2003

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

First-order Draft

- 2385 L. P. Ni, V. L. Rayzman. Combined ways of processing low-quality aluminum raw materials. Monograph, Science,
2386 Alma-Ata, Bibliography, pp. 252-253 (1988).
- 2387 S. Y. Dancing, E. D. Andreeva, V. V. Pivovarov and others. Nepheline rocks are a complex aluminum raw material.
2388 - monograph. - Bowels. Moscow. (1988).
- 2389 L. P. Ni. Alkaline hydrochemical methods for processing high-silicon bauxites. Science, Alma-Ata, Bibliography,
2390 pp. 134-138 (1967)
- 2391 I. V. Loginova, A. V. Kirchikov. Alumina production. Textbook of Ural Polytechnic University. Ekaterinburg,
2392 (2010).
- 2393 Alumina Extraction from Non Bauxitic Materials. D.J. O'Connor Germany, Aluminium Verlag, 1988 (385
2394 p.)
- 2395 Alumina Production in Russia Part I: Historical Background, V. Smirnov, JOM, 48 (8) (1996), pp. 24-26.
- 2396 Physical-chemical fundamentals of alumina production from nepheline. M. N. Smirnov. Proceedings of the
2397 Second International Symposium of ICSOBA, Vol. 3 pp. 337-345 (1971).
- 2398 G. Baudet. A documentary study on alumina extraction process, Service Geologique National (1977).
2399 <http://infoterre.brgm.fr/rapports/77-SGN-061-MIN.pdf>
- 2400 John W. Hosterman, Sam H. Patterson, and Elizabeth E. Good, World Nonbauxite Aluminum Resources
2401 Excluding Alunite, U.S. geological survey professional paper, 1076-C, Washington, (1990).
- 2402 M. N. Smirnov, Physical-chemical fundamentals of alumina production from nepheline, Proceedings of the Second
2403 International Symposium of ICSOBA, Vol. 3 pp. 337-345 (1971)
- 2404 Vadim Smirnov, Alumina Production in Russia Part I: Historical Background, JOM, 48 (8) (1996), pp. 24-26.
- 2405 Bardai, A., Aga, B. E., Berveling, A., Droste, C., Fechner, M., Haugland, E., Karlsen, M., Liane, M., Ryman, S.
2406 O., Vee, T. H., Wedershoven, E. & Ovstetun, F. (2009) HAL 4e - Hydro's new generation cell technology.
2407 In: *Light Metals*.
- 2408 Dando, N. R., Menegazzo, N., Espinoza-Nava, L., Westendorf, N. & Batista, E. (2015) Non anode effects PFC :
2409 Measurement consideration and potential impact. In: *Light Metals*, pp. 551-555. Orlando.
- 2410 Dion, L., Marks, J., Kiss, L.I., Poncsak, S., Lagacé, C-L., (2017) Quantification of perfluorocarbon emissions
2411 during high voltage anode effects using non-linear approach. In: *Journal of Cleaner Production*, **164**: 357-
2412 366.
- 2413 Dion, L., Wong, D. S., Nunez, P., Gaboury, S. & Spirin, A. V. (2018) Evaluation of time consistency when
2414 quantifying emissions of perfluorocarbons resulting from low voltage anode effects. In: *Light Metals*,
2415 Phoenix, AZ, USA.
- 2416 Emirates Global Aluminium. (2017) Reduction Cell Technologies. URL
2417 <https://www.ega.ae/en/technology/reduction-cell-technologies/>.
- 2418 International Aluminium Institute. (2006) The aluminium sector greenhouse gas protocol. 65 pages.
- 2419 Marks, J. & Bayliss, C. (2012) GHG measurement and inventory for aluminium production. In : *Light Metals*, pp.
2420 805-808.
- 2421 Marks, J. & Nunez, P. (2018) Updated Factors for Calculating PFC Emissions from Primary Aluminum Production.
2422 In: *Light Metals*, Phoenix, AZ.
- 2423 Rio Tinto Alcan. (2013) AP Technology - Our products and services. URL [https://www.ap-](https://www.ap-technology.com/SitePages/products.aspx)
2424 [technology.com/SitePages/products.aspx](https://www.ap-technology.com/SitePages/products.aspx).
- 2425 Tabereaux, A. (2004) Anode effects and PFC emissions rates. In: *8th australasian aluminium smelting technology*
2426 *conference*.
- 2427 US Environmental Protection Agency & International Aluminium Institute. (2008) Protocol for Measurement of
2428 Tetrafluoromethane (CF₄) and Hexafluoroethane (C₂F₆) Emissions from Primary Aluminum Production.
2429 42 pages.
- 2430 Wong, D. & Marks, J. (2013) Continuous PFC emissions measured on individual 400 kA cells. In: *Light Metals*,
2431 pp. 865-870. San Antonio.
- 2432 Wong, D. S., Fraser, P., Lavoie, P. & Kim, J. (2015) PFC emissions from detected versus nondetected anode
2433 effects in the aluminium industry. *JOM* **67**(2): 342-353.

- Xiping, C., Wangxing, L., Yanfang, Z., Shilin, Q. & Bayliss, C. (2013) Investigation on formation mechanism of non-anode effect related PFC emissions from aluminum reduction cells. In: *TMS Light Metals*, pp. 877-881.
- Zarouni, A. A., Reverdy, M., Zarouni, A. & Vankatasubramaniam, K. G. (2013) A study of low voltage PFC emissions at DUBAL. In: *Light Metals*, pp. 859-863. San Antonio.
- SECTION 4.8**
- International Aluminium Institute. (2006) The aluminium sector greenhouse gas protocol. 65 pages.
- Liu, K.-r., Chen, J.-s. & Wei, X.-j. (2001) Analysis of anodic gases in neodymium electrolysis. *The Chinese Journal of Nonferrous Metals* **11**(6): 1118-1120.
- US Environmental Protection Agency & International Aluminium Institute. (2008) Protocol for Measurement of Tetrafluoromethane (CF₄) and Hexafluoroethane (C₂F₆) Emissions from Primary Aluminum Production. 42 pages.
- Vogel, H., Flerus, B., Stoffner, F. & Friedrich, B. (2016) Reducing Greenhouse Gas Emission from the Neodymium Oxide Electrolysis. Part I: Analysis of the Anodic Gas Formation. *Journal of Sustainable Metallurgy* **3**(1): 99-107.
- Vogel, H. & Friedrich, B. (2015) Development and Research Trends of the Neodymium Electrolysis – A Literature Review. In: *8th European Metallurgical Conference (EMC)*, Dusseldorf, Germany.
- Vogel, H. & Friedrich, B. (2018) An estimation of PFC emissions by rare earth electrolysis. In: *Light Metals*, Phoenix.
- Wen, H., Kuang, G. & Mao, J. (2004) Circular 10 kA molten salt electrolyzer for preparing rare earth metal. In: ed. China's State Intellectual Property Office, pp. 1-7. China: Ganzhou Keli Rare Earth New Materials Co., Ltd.
- Wen, H., Kuang, G. & Mao, J. (2012) 25 KA rare earth electrolytic cell for fluoride molten salt system. In: ed. China's State Intellectual Property Office, pp. 1-6. China.
- Zhang, L., Wang, X. & Gong, B. (2017) Perfluorocarbon emissions from electrolytic reduction of rare earth metals in fluoride/oxide system. *Atmospheric Pollution Research*.