CHAPTER 4

METAL INDUSTRY EMISSIONS

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4 METAL INDUSTRY EMISSIONS

4.1 INTRODUCTION

The following sections 4.2 through 4.7 give guidance for estimating greenhouse gas emissions that result from the production of metals.

- Section 4.2 covers emissions from iron and steel, and metallurgical coke production;
- Section 4.3 covers emissions from ferroalloy production;
- Section 4.4 covers emissions from aluminium production;
- Section 4.5 covers emissions from magnesium production;
- Section 4.6 covers emissions from lead production;
- Section 4.7 covers emissions from zinc production.

Care should be exercised to avoid double counting of carbon dioxide (CO_2) emissions in both this chapter and in Volume 2 on Energy Sector, or, in omitting CO_2 emissions since CO_2 emissions resulting from carbon's role as process reactant and as a heat source to drive the chemical reactions involved in the metallurgical processes are closely related in many cases. Should CO_2 capture technology be installed at a metals production facility, the CO_2 captured should be deducted in a higher tier emissions calculation. Any methodology taking into account CO_2 capture should consider that CO_2 emissions captured in the process may be both combustion and process-related. In cases where combustion and process emissions are to be reported separately, e.g., for iron and steel production, inventory compilers should ensure that the same quantities of CO_2 are not double counted. In these cases the total amount of CO_2 captured should preferably be reported in the corresponding energy combustion and IPPU source categories in proportion to the amounts of CO_2 generated in these source categories. The default assumption is that there is no CO_2 capture and storage (CCS) taking place. For additional information on CO_2 capture and storage refer to Volume 3, Section 1.2.2 and for more details to Volume 2, Section 2.3.4.

4.2 IRON & STEEL AND METALLURGICAL COKE PRODUCTION

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

The iron and steel industry broadly consists of:

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

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

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

Primary and secondary steel-making:
Steel production can occur at integrated facilities from iron ore, or at secondary facilities, which produce steel mainly from recycled steel scrap. Integrated facilities typically include coke production, blast furnaces, and 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).

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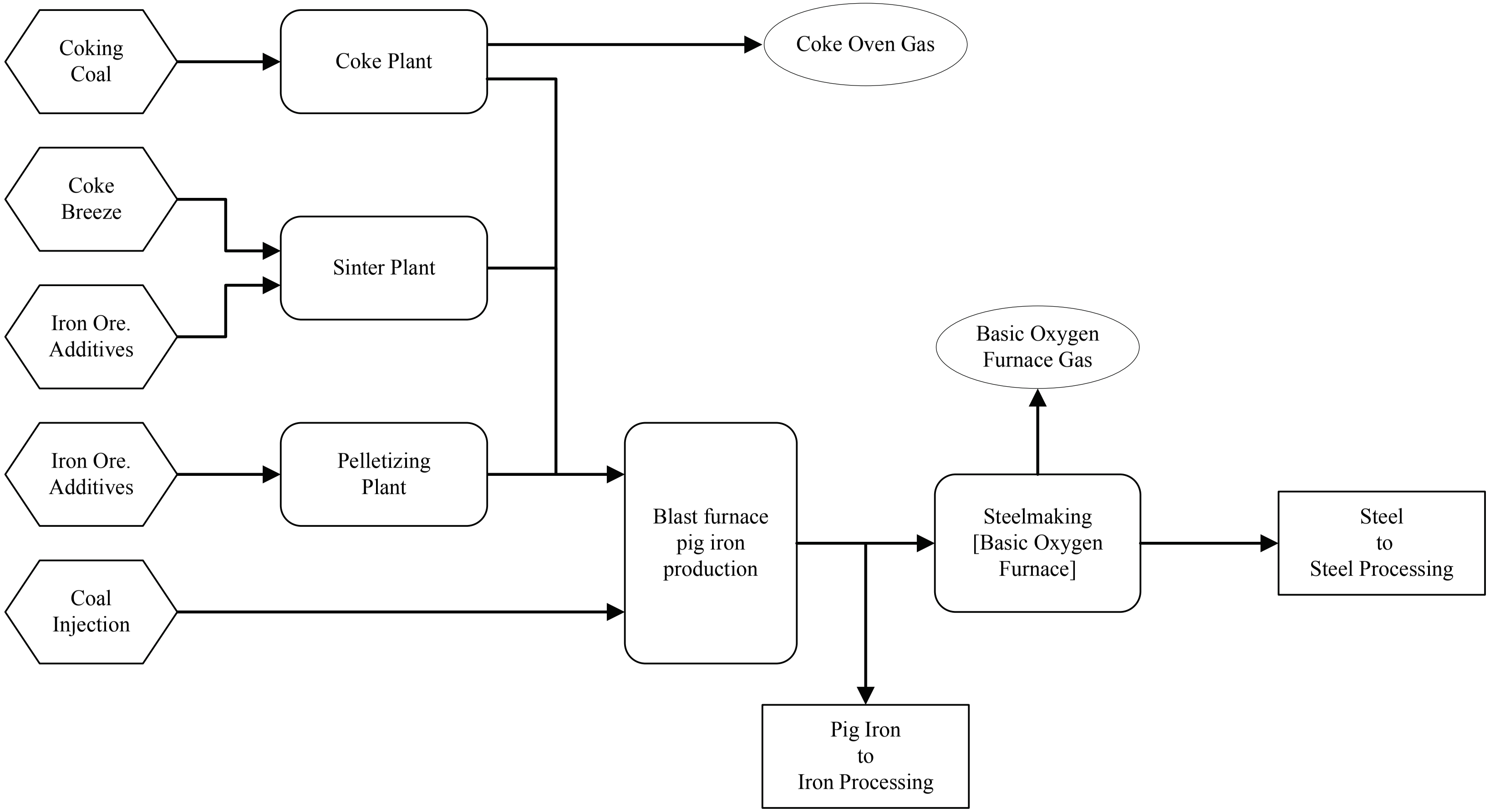
[1] No methodologies are provided for N_2O emissions. These emissions are likely to be small, but countries can calculate estimates provided they develop country-specific methods based on researched data.

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



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

4.2.1 Introduction

METALLURGICAL COKE PRODUCTION

Metallurgical coke is primarily used in the blast furnace to make iron. Coke is also used in other metallurgical processes, such as the manufacture of cast iron, ferroalloys, lead, and zinc, and in kilns to make lime and magnesium. Metallurgical coke is the solid product obtained from the carbonisation of coal, principally coking coal, at high temperature. It is low in moisture content and volatile matter. Coking coal refers to bituminous coal with a quality that allows the production of a coke suitable to support a blast furnace charge. Its gross calorific value is greater than 23 865 kJ/kg (5 700 kcal/kg) on an ash-free but moist basis. Coke oven gas is a by-product of the manufacture of metallurgical coke for the production of iron and steel. Figure 4.2 illustrates the coke production process and associated sources of CH_4 and CO_2 emissions.

Note that coke oven gas may be burned to heat coke ovens or transferred onsite in an integrated iron and steel plant and used in sinter production or iron production processes. Coke oven gas may also be transferred off site (e.g., into the natural gas distribution system) and used as an energy source. The combustion of coke in blast furnaces during the iron and steel-making process produces blast furnace gas, which may then be recovered and transferred from the iron and steel mill to the onsite coke plant and burned to heat coke ovens or used in sinter production. The combustion of blast furnace gas and coke oven gas is the main sources of CO_2 and CH_4 emissions in coke production.

SINTER PRODUCTION

Iron ore and other iron-containing materials may be agglomerated in sinter plants at integrated iron and steel plants prior to introduction into the blast furnace. Feedstock to sinter plants may include fine iron ores, additives (e.g., lime, olivine), and iron-bearing recycled materials from downstream iron and steelmaking processes (e.g., dust from blast-furnace gas cleaning). Coke breeze (small-grade coke oven coke with particle sizes of < 5 mm) is the most commonly used process material in sinter plants. The coke breeze may be produced from the onsite coke ovens in integrated iron and steel plants, or may be purchased from offsite coke producers. Blast furnace gas or coke oven gas produced onsite during integrated iron and steel production may be used in sinter plants. Operation of sinter plants produces carbon dioxide emissions from oxidation of the coke breeze and other inputs. Off gas from sinter production also contains methane and other hydrocarbons. Figure 4.3 illustrates the sinter production process.

PELLET PRODUCTION

Pellets are formed from iron-containing raw materials (i.e., fine ore and additives) into 9-16 mm spheres in a very high temperature process. The process includes grinding, drying, balling, and thermal treatment of the raw materials. Pelletisation plants are principally located at iron mines or at shipping ports, but can also be located onsite as part of an integrated iron and steel facility. Natural gas or coal may be used as fuel for pelletisation plants; for pelletisation plants located onsite at an integrated iron and steel facility, coke oven gas may be used as a fuel. Energy consumption for the process and the associated CO_2 emissions will depend in part on the quality of the iron ore and other raw materials used in the process. The CO_2 emissions will also depend upon the carbon contents and heating values of fuels used in the process.

IRONMAKING AND THE ROLE OF COKE

Most CO_2 emitted by the iron and steel industry is associated with the production of iron, more specifically the use of carbon to convert iron ore to iron. Figure 4.4 describes the iron-making process and associated sources of emissions. Carbon is supplied to the blast furnace mainly in the form of coke produced from metallurgical grade coking coal (but can also be in the form charcoal made from wood or other forms of carbon.). Carbon serves a dual purpose in the iron making process, primarily as a reducing agent to convert iron oxides to iron, but also as an energy source to provide heat when carbon and oxygen react exothermically. Blast furnace gas is produced during the combustion of coke in blast furnaces. It is typically recovered and used as a fuel partly within the plant and partly in other steel industry processes, or in power stations equipped to burn it. Blast furnace gas may also be recovered and transferred from the iron and steel mill to the onsite coke plant and burned for energy within the coke ovens. Blast furnace gas may also be transferred offsite and used as an energy source both within the furnace and when blast furnace gas is combusted to heat blast air. Oxygen steel furnace gas is obtained as a by-product of the production of steel in a basic oxygen furnace (BOF) and is recovered on leaving the furnace. All carbon used in blast furnaces should be considered process-related IPPU emissions.

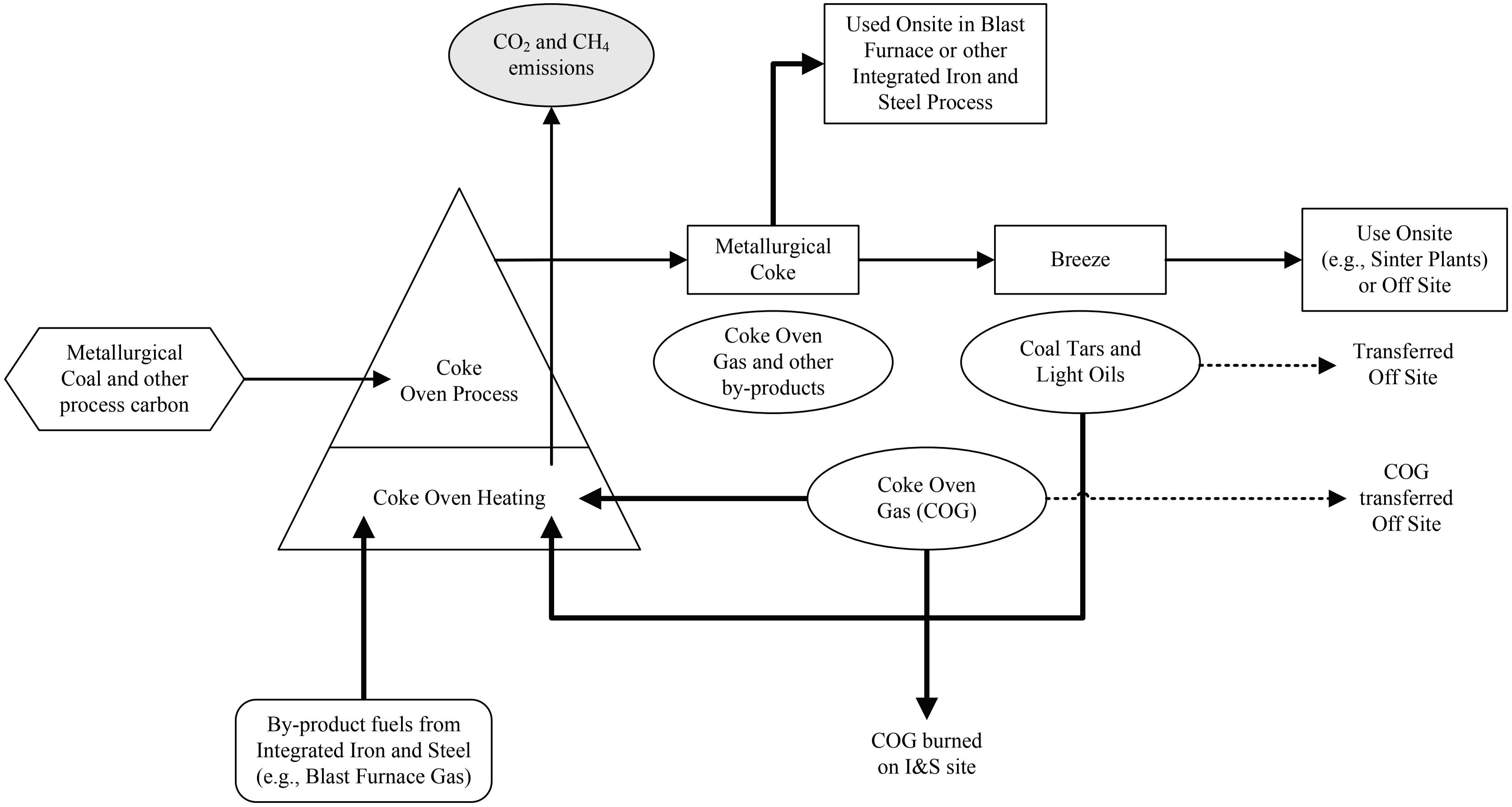
Additionally, iron can be produced through a direct reduction process. Direct reduction involves the reduction of iron ore to metallic iron in the solid state at process temperatures less than 1 000°C. A solid product referred to as direct reduced iron (DRI) is produced by the direct reduction process. DRI has a carbon content of < 2 percent. DRI is normally used as a replacement for scrap metal in the electric arc furnace steelmaking route, but may also be used as a feedstock for blast furnace iron making. DRI may also be melted into briquettes, referred to as hot briquetted iron (HBI), when the product has to be stored or transported. Inventory preparers can estimate the CO_2 emissions from these processes from the energy consumption and carbon content of the fuel (e.g., natural gas, coal).

STEELMAKING

Steel production in a BOF begins by charging the vessel with 70-90 percent molten iron and 10-30 percent steel scrap. High purity oxygen then combines with the carbon in the iron to create an exothermic reaction that melts the charge while lowering the carbon content. Iron from the blast furnace usually contains 3-4 percent carbon, which must be reduced to less than 1 percent, refined, and alloyed to produce the desired grade of steel.

Steel production in an EAF typically occurs by charging 100 percent recycled steel scrap, which is melted using electrical energy imparted to the charge through carbon electrodes and then refined and alloyed to produce the desired grade of steel. Although EAFs may be located in integrated plants, typically they are stand-alone operations because of their fundamental reliance on scrap and not iron as a raw material. Since the EAF process is mainly one of melting scrap and not reducing oxides, carbon’s role is not as dominant as it is in the blast furnace/BOF process. In a majority of scrap-charged EAF, CO_2 emissions are mainly associated with consumption of the carbon electrodes. All carbon used in EAFs and other steelmaking processes should be considered process-related IPPU emissions. Figure 4.5 illustrates the steel making process and associated sources of emissions.

Figure 4.2 **Illustration of coke production process (emissions reported in Category 1A of the Energy Sector)**



Note:
Bold lines apply only to Onsite Coke Production at Integrated Iron and Steel Mill. Dashed lines apply to transfers of materials to 'Off Site processes.' 'Off Site process' does not include Integrated Iron and Steel production processes, which are categorised as Onsite.

Figure 4.3 Illustration of sinter production process

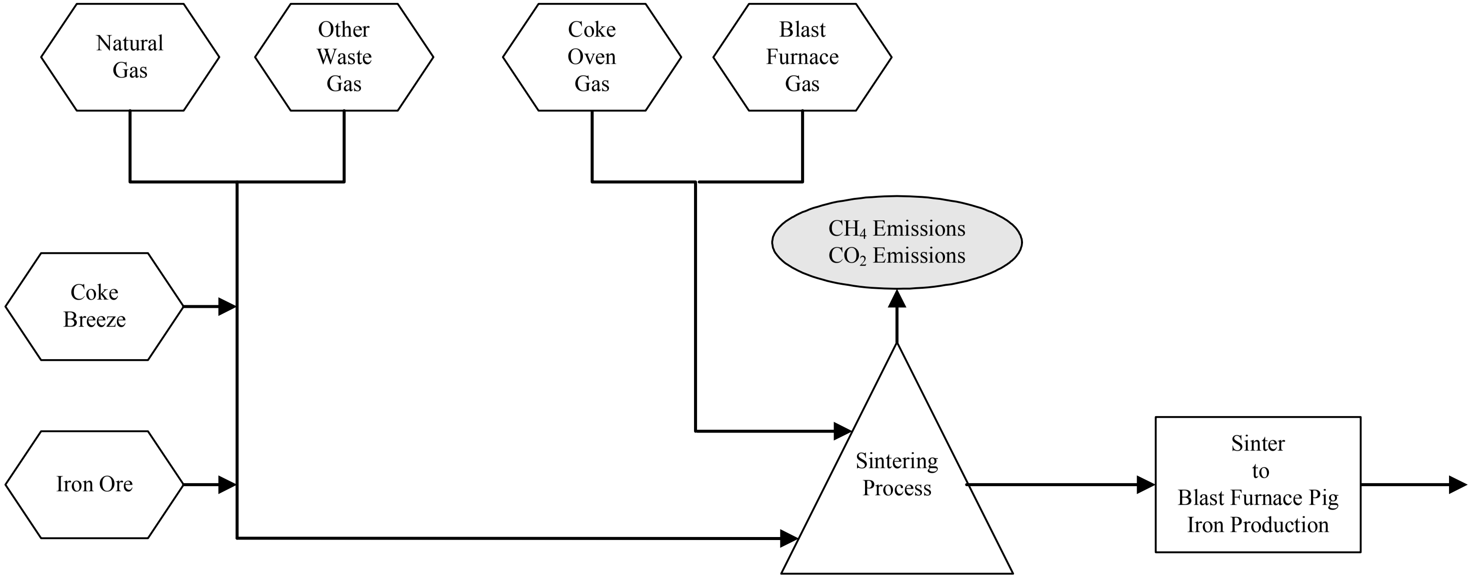


Figure 4.4 **Illustration of pig iron production processes**

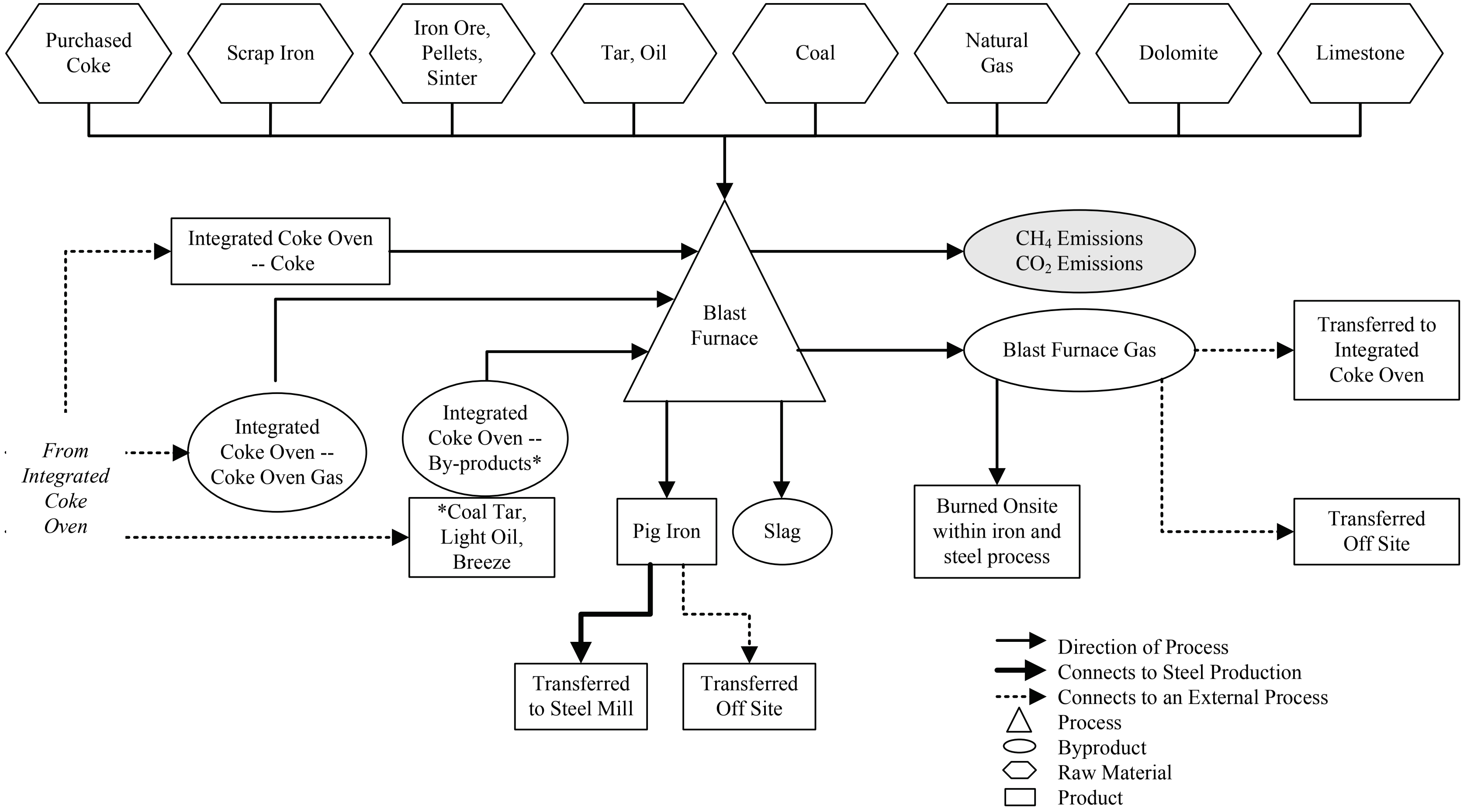
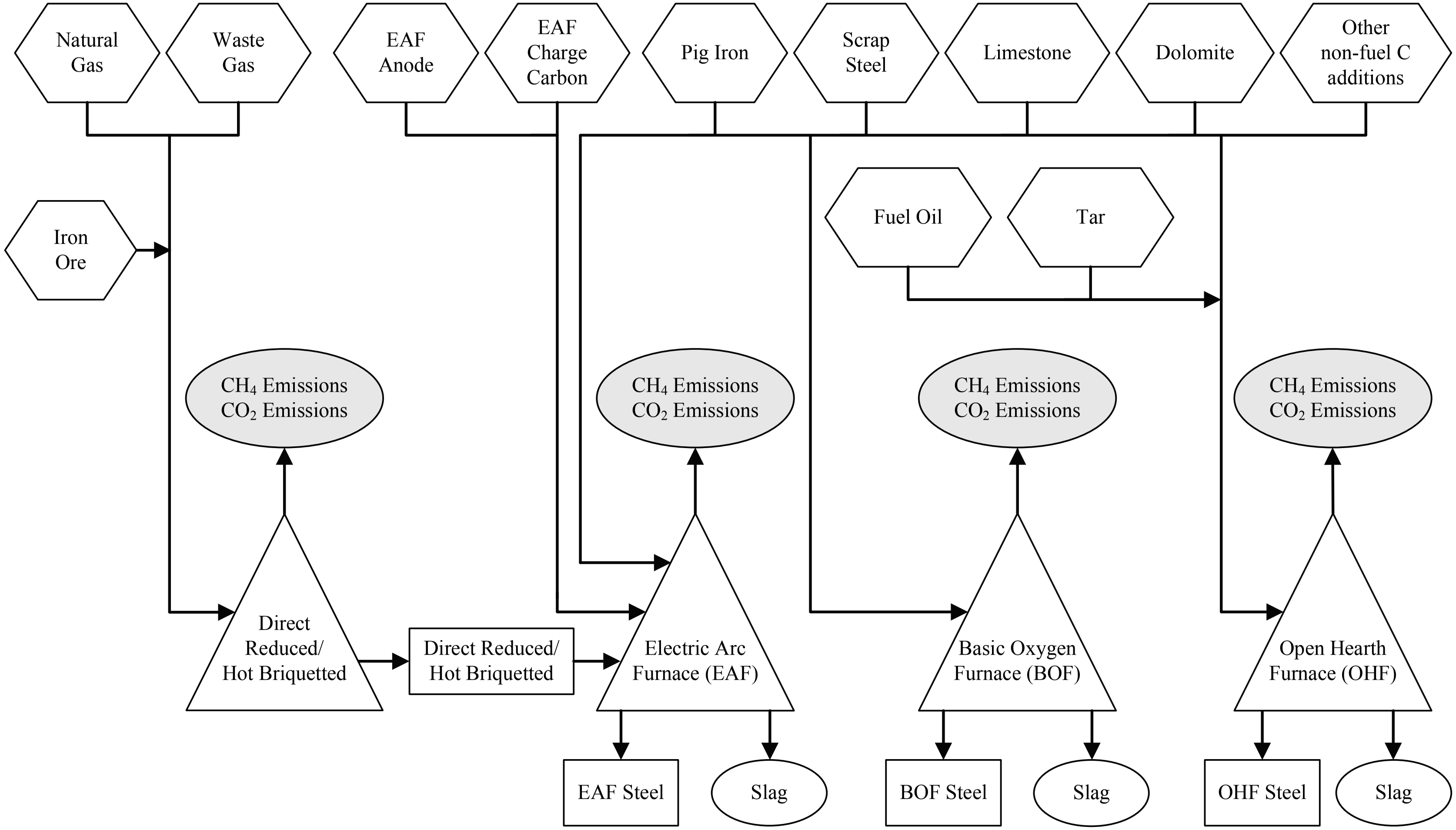


Figure 4.5 Illustration of steel production processes



4.2.2 Methodological issues

4.2.2.1 CHOICE OF METHOD: METALLURGICAL COKE PRODUCTION

The *IPCC Guidelines* outline three tiers for calculating CO_2 emissions and two tiers for calculating CH_4 emissions from coke production. The choice of a *good practice* method for estimation of CO_2 emissions depends on national circumstances as shown in the decision tree in Figure 4.6 Estimation of CO_2 Emissions from Metallurgical Coke Production. For CH_4 emissions, use the decision tree in Figure 4.8.

Metallurgical coke is produced either at the iron and steel facility ('onsite') or at separate facilities ('offsite').The Tier 1 method calculates emissions from all coke production using default emission factors applied to national coke production.

The Tier 2 method for estimating CO_2 emissions distinguishes between onsite and offsite coke production. It uses national activity data for the consumption and production of process materials (e.g., coking coal consumed, coke produced, and coal tar products produced). As discussed above, the Tier 2 method is not applicable to estimating CH_4 emissions. The Tier 3 method requires plant-specific CO_2 emissions data and plant-specific CH_4 emissions data, or plant-specific activity data.

TIER 1 METHOD – PRODUCTION-BASED EMISSION FACTORS

Equation 4.1 calculates emissions from all coke production. The Tier 1 method assumes that all coke made onsite at iron and steel production facilities is used onsite. The Tier 1 method is to multiply default emission factors by tonnes of coke produced. Emissions should be reported in the Energy Sector.

EQUATION 4.1
EMISSIONS FROM COKE PRODUCTION (TIER 1)

$$E_{CO2} = Coke \bullet EF_{CO2} \text{ and } E_{CH4} = Coke \bullet EF_{CH4} \quad \text{(To be reported in Energy Sector)}$$

Where:

E_{CO2} or E_{CH4} = emissions of CO_2 or CH_4 from coke production, tonnes CO_2 or tonnes CH_4

Coke = quantity of coke produced nationally, tonnes

EF= emission factor, tonnes CO_2/tonne coke production or tonnes CH_4/tonne coke production

Note: The Tier 1 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.

TIER 2 METHOD

The Tier 2 method is appropriate if national statistics on process inputs and outputs from integrated and non-integrated coke production processes are available. Tier 2 will produce a more accurate estimate than Tier 1 because it takes into account the actual quantity of inputs into and outputs rather than making assumptions.

As expressed in Equations 4.2 and 4.3, Tier 2 estimates CO_2 emissions from onsite coke production separately from off-site production. This separation is due to overlapping data requirements when estimating emissions from onsite coke production and emissions from iron and steel production.

EQUATION 4.2
CO_2 EMISSIONS FROM ONSITE COKE PRODUCTION (TIER 2)

$$E_{CO2,\, energy} = \Big[CC \bullet C_{CC} + \sum_a \left(PM_a \bullet C_a \right) + BG \bullet C_{BG} - CO \bullet C_{CO} - COG \bullet C_{COG} - \sum_b \left(COB_b \bullet C_b \right) \Big] \bullet \frac{44}{12}$$

Where:

$E_{CO2,\, energy}$ = emissions of CO_2 from onsite coke production to be reported in Energy Sector, tonnes

CC = quantity of coking coal consumed for coke production in onsite integrated iron and steel production facilities, tonnes

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 onsite coke production and iron and steel production facilities, tonnes

BG = quantityof blast furnace gas consumed in coke ovens, m^3 (or other unit such as tonnes or GJ. Conversion of the unit should be consistent with Volume 2: Energy)

CO = quantity of coke produced onsite at iron and steel production facilities, tonnes

COG = quantity of coke oven gas transferred offsite , m^3 (or other unit such as tonnes or GJ. Conversion of the unit should be consistent with Volume 2: Energy)

COB_b = quantity of coke oven by-product *b*, transferred offsite either to other facilities, tonnes

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

For offsite coke production, the inventory compiler should use Equation 4.3. Total emissions are the sum of emissions from all plants using both Equations 4.2 and 4.3.

EQUATION 4.3
CO_2 EMISSIONS FROM OFFSITE COKE PRODUCTION (TIER 2)

$$E_{CO2,energy} = \left[CC \bullet C_{CC} + \sum_a \left(PM_a \bullet C_a \right) - NIC \bullet C_{NIC} - COG \bullet C_{COG} - \sum_b \left(COB_b \bullet C_b \right) \right] \bullet \frac{44}{12}$$

Where:

$E_{CO2,\ energy}$ = emissions of CO_2 from offsite coke production to be reported in Energy Sector, tonnes

CC = quantity of coking coal used in non-integrated coke production facilities, tonnes

PM_a = quantity of other process material *a*, other than coking coal, such as natural gas, and fuel oil consumed nationally in non-integrated coke production, tonnes

NIC = quantity of coke produced offsite in non-integrated coke production facilities nationally, tonnes

COG = quantity of coke oven gas produced in offsite non-integrated coke production facilities nationally that is transferred to other facilities, m^3 (or other unit such as tonnes or GJ. Conversion of the unit should be consistent with Volume 2: Energy)

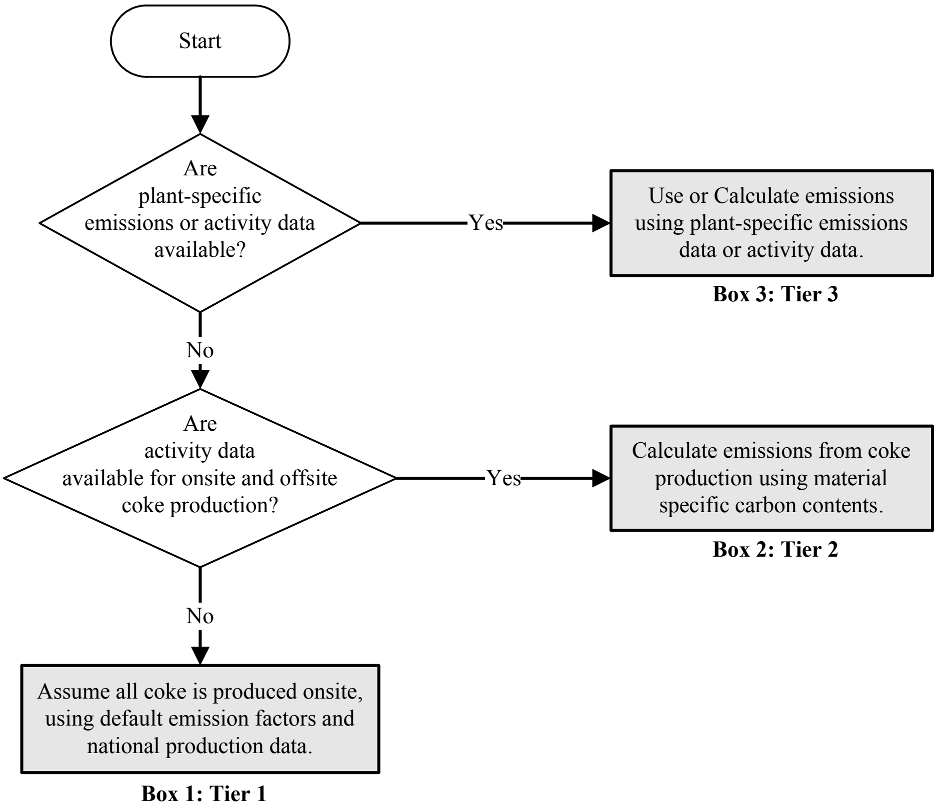
COB_b= quantity of coke oven by-product *b*, produced nationally in offsite non-integrated facilities and transferred offsite to other facilities, tonnes

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

TIER 3 METHOD

Unlike the Tier 2 method, the Tier 3 method uses plant specific data because plants can differ substantially in their technology and process conditions. If actual measured CO_2/CH_4 emissions data are available from onsite and offsite coke production plants, these data can be aggregated and used directly to account for national emissions from metallurgical coke production using the Tier 3 method. Total national emissions will equal the sum of emissions reported from each facility. If facility-specific CO_2 emissions data are not available, CO_2 emissions can be calculated from plant-specific activity data applying the Tier 2 method, Equations 4.2 and 4.3. Total national emissions will equal the sum of emissions reported from each facility.

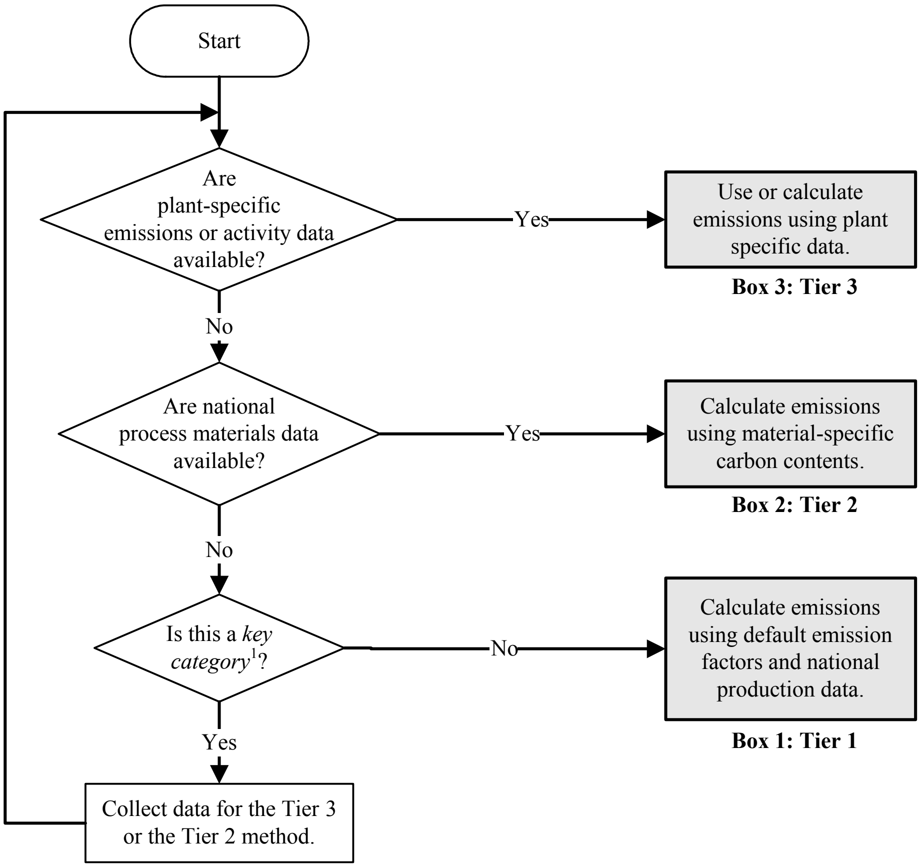
Figure 4.6 Estimation of CO_2 emissions from metallurgical coke production



4.2.2.2 CHOICE OF METHOD: IRON AND STEEL PRODUCTION

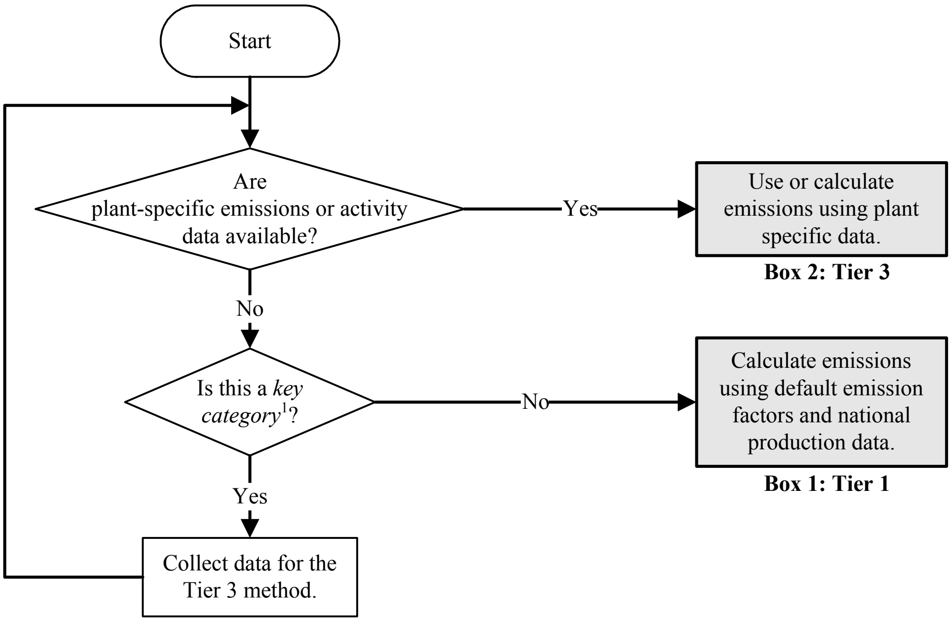
These *Guidelines* outline three tiers for calculating CO_2 emissions and two tiers for calculating CH_4 emissions from iron and steel production. The choice of a *good practice* method depends on national circumstances as shown in the decision tree in Figure 4.7 for CO_2 emissions and Figure 4.8 for CH_4 emissions: Decision Tree for Estimation of CO_2 Emissions from Iron & Steel Production and Decision Tree for Estimating of CH_4 Emissions from Iron and Steel Production. The Tier 1 method is based on national production data and default emission factors. It may lead to errors due to its reliance on assumptions rather than actual data for the quantity of inputs into the sinter production and iron and steel production sector that contribute to CO_2 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 CO_2 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 CH_4 emissions. The Tier 3 method requires plant-specific emissions or activity data aggregated to the national level for estimating CO_2 and CH_4 emissions.

Figure 4.7 Decision tree for estimation of CO_2 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 CH_4 emissions from iron and steel production



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

METHODOLOGY FOR ESTIMATING CO_2 EMISSIONS

Tier 1 method – production-based emission factors

The Tier 1 approach for emissions from iron and steel production is to multiply default emission factors by national production data, as shown in Equation 4.4. Because emissions per unit of steel production vary widely depending on the method of steel production, it is *good practice* to determine the share of steel produced in different types of steelmaking processes, calculate emissions for each process, and then sum the estimates. Equation 4.4 considers steel production from 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 that is not converted into steel. It is preferable to estimate emissions from this production separately because the emission factors for integrated iron and steel production (BOF and OHF processes) take into account emissions from both steps.

Equation 4.6 calculates CO_2 emissions from production of Direct Reduced Iron (DRI) for the Tier 1 method using a CO_2 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
CO_2 EMISSIONS FROM IRON AND STEEL PRODUCTION (TIER 1)

$$\text{Iron \& Steel: } E_{CO2,\ non-energy} = BOF \bullet EF_{BOF} + EAF \bullet EF_{EAF} + OHF \bullet EF_{OHF}$$

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

$$\text{Pig Iron Production: } E_{CO2,\ non-energy} = IP \bullet EF_{IP}$$

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

$$\text{Direct Reduced Iron: } E_{CO2,\ non-energy} = DRI \bullet EF_{DRI}$$

EQUATION 4.7
CO_2 EMISSIONS FROM SINTER PRODUCTION (TIER 1)

$$\text{Sinter Production: } E_{CO2,\ non-energy} = SI \bullet EF_{SI}$$

EQUATION 4.8
CO_2 EMISSIONS FROM PELLET PRODUCTION (TIER 1)

$$\text{Pellet Production: } E_{CO2,\ non-energy} = P \bullet EF_{P}$$

Where:

$E_{CO2,\ non-energy}$ = emissions of CO_2 to be reported in IPPU Sector, tonnes

BOF= quantity of BOF crude steel produced, tonnes

EAF = quantity of EAF crude steel produced, tonnes

OHF = quantity of OHF crude steel produced, tonnes

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

DRI = quantity of Direct Reduced Iron produced nationally, tonnes

SI = quantity of sinter produced nationally, tonnes

P = quantity of pellet produced nationally, tonnes

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

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 CO_2 emissions.

In calculating pellet production emissions, energy consumption and heating value and carbon content of the fuel can be used similarly to the other methodologies.

EQUATION 4.9

CO_2 EMISSIONS FROM IRON & STEEL PRODUCTION (TIER 2)

$$E_{CO2,non-energy} = \Big[PC \bullet C_{PC} + \sum_a \left(COB_a \bullet C_a \right) + CI \bullet C_{CI} + L \bullet C_L + D \bullet C_D + CE \bullet C_{CE} + \sum_b \left(O_b \bullet C_b \right) + COG \bullet C_{COG} - S \bullet C_S - IP \bullet C_{IP} - BG \bullet C_{BG} \Big] \bullet \frac{44}{12}$$

EQUATION 4.10

CO_2 EMISSIONS FROM SINTER PRODUCTION (TIER 2)

$$E_{CO2,non-energy} = \Big[CBR \bullet C_{CBR} + COG \bullet C_{COG} + BG \bullet C_{BG} + \sum_a \left(PM_a \bullet C_a \right) - SOG \bullet C_{SOG} \Big] \bullet \frac{44}{12}$$

Where, for iron and steel production:

$E_{CO2,\ non\text{-}energy}$ = emissions of CO_2 to be reported in IPPU Sector, tonnes

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

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

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

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

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

CE = quantity of carbon electrodes consumed in EAFs, tonnes

O_b = quantity of other carbonaceous and process material *b*, consumed in iron and steel production, such as sinter or waste plastic, tonnes

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

S = quantity of steel produced, tonnes

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

BG = quantity of blast furnace gas transferred offsite, m^3 (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:

$E_{CO2,\ non\text{-}energy}$ = emissions of CO_2 to be reported in IPPU Sector, tonnes

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

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

BG = quantity of blast furnace gas consumed in sinter production, m^3 (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, tonnes

SOG = quantity of sinter off gas transferred offsite either to iron and steel production facilities or other facilities, m^3 (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]

Equation 4.11 calculates CO_2 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

CO_2 EMISSIONS FROM DIRECT REDUCED IRON PRODUCTION (TIER 2)

$$E_{CO2,non-energy} = \left(DRI_{NG} \bullet C_{NG} + DRI_{BZ} \bullet C_{BZ} + DRI_{CK} \bullet C_{CK}\right) \bullet \frac{44}{12}$$

Where:

$E_{CO2,\ non\text{-}energy}$ = emissions of CO_2 to be reported in IPPU Sector, tonnes

DRI_{NG} = amount of natural gas used in direct reduced iron production, GJ

DRI_{BZ} = amount of coke breeze used in direct reduced iron production, GJ

DRI_{CK} = amount of metallurgical coke used in direct reduced iron production, GJ

C_{NG} = carbon content of natural gas, tonne C/GJ

C_{BZ} = carbon content of coke breeze, tonne C/GJ

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

Tier 3 method

Unlike the Tier 2 method, the Tier 3 method uses plant specific data. The Tier 3 method provides an even more accurate estimate of emission than the Tier 2 method because plants can differ substantially in their technology and process conditions. If actual measured CO_2 emissions data are available from iron and steelmaking facilities, these data can be aggregated to account for national CO_2 emissions. If facility-specific CO_2 emissions data are not available, CO_2 emissions can be calculated from plant-specific activity data for individual reducing agents, exhaust gases, and other process materials and products. Total national emissions will equal the sum of emissions reported from each facility. Equations 4.9 through 4.11 describe the parameters that are necessary for an accounting of plant-specific emissions using the Tier 3 method and plant-specific activity data at a facility level. Plant-specific carbon contents for each material are required for the Tier 3 method.

METHODOLOGY FOR CH_4

When carbon-containing materials are heated in the furnace for sinter production or iron production, the volatiles, including methane, are released. With open or semi-covered furnaces, most of the volatiles will burn to CO_2 above the charge, in the hood and off-gas channels, but some will remain un-reacted as CH_4 and non-methane volatile organic compounds (NMVOC). The amounts depend on the operation of the furnace. Sprinkle-charging will reduce the amounts of CH_4 compared to batch-wise charging. Increased temperature in the hood (less false air) will reduce the content of CH_4 further.

This section describes a Tier 1 default method and a more advanced Tier 3 facility-level method for CH_4 from sinter production or iron production, both of which are similar to the approaches described for estimating CO_2 emissions. There is no Tier 2 method. CH_4 may be emitted from steel–making processes as well, however those emissions are assumed to be negligible. Therefore CH_4 emissions from steel-making processes are not discussed here.

The Tier 1 methodology for CH_4 is based on emission factors and national production statistics.

EQUATION 4.12
CH_4 EMISSIONS FROM SINTER PRODUCTION (TIER 1)

$$\text{Sinter Production: } E_{CH4,\ non-energy} = SI \bullet EF_{SI}$$

EQUATION 4.13
CH_4 EMISSIONS FROM BLAST FURNACE PRODUCTION OF PIG IRON (TIER 1)

$$\text{Pig Iron Production: } E_{CH4, non-energy} = PI \bullet EF_{PI}$$

EQUATION 4.14
CH_4 EMISSIONS FROM DIRECT REDUCED IRON PRODUCTION (TIER 1)

$$\text{Direct Reduced Iron Production: } E_{CH4, non-energy} = DRI \bullet EF_{DRI}$$

Where:

$E_{CH4,\ non\text{-}energy}$ = emissions of CH_4 to be reported in IPPU Sector, kg

SI = quantity of sinter produced nationally, tonnes

PI = quantity of iron produced nationally including iron converted to steel and not converted to steel, tonnes

DRI = quantity of direct reduced iron produced nationally, tonnes

EF_x = emission factor, kg CH_4/tonne *x* produced

The Tier 3 method uses plant specific emissions data. If actual measured CH_4 emissions data are available for coke production, these data can be aggregated to account for national CH_4 emissions. Total national emissions will equal the sum of emissions reported from each facility.

4.2.2.3 CHOICE OF EMISSION FACTORS

TIER 1 METHOD

Carbon dioxide emission factors

Table 4.1 provides default emission factors for coke, sinter, pellet, iron, and steel production. The emission factors for the three steelmaking methods are based on expert judgment using typical practice for the different steel production scenarios listed. The default emission factors account for all carbon input into the blast furnace. It is assumed based on the Integrated Pollution Prevention and Control (IPPC) Reference Document on Production of Iron and Steel (European IPPC Bureau, 2001) (referred to in this section as 'IPPC I&S BAT Document') that most of the carbon input to the blast furnace is from coke (60 -90 percent).

The default CO_2 emission factor for coke production is derived by averaging plant-specific CO_2 emissions data for 11 European coke plants reported in the IPPC I&S BAT Document. Emissions of CO_2 are reported in Table 6.2 of the IPPC I&S BAT Document in units of kilograms of CO_2 per tonne of liquid steel produced. The CO_2 emissions range from 175 to 200 kg CO_2 per tonne liquid steel. The conversion factors provided in Table 6.2 of the IPPC Document are 940 kg pig iron per tonne liquid steel and 358 kg coke per tonne pig iron. Based on these conversion factors the average CO_2 emissions from the 11 European coke plants is 0.56 tonne CO_2 per tonne coke produced.

The CO_2 emission factor for sinter plants is derived by averaging plant-specific CO_2 emissions data for four European sinter plants reported in the IPPC I&S BAT Document. Emissions of CO_2 are reported in Table 4.1 of the IPPC I&S BAT Document in units of kilograms of CO_2 per tonne of liquid steel produced. The CO_2 emissions range from 205 to 240 kg CO_2 per tonne liquid steel. The conversion factors provided in Table 4.1 of the IPPC I&S BAT Document are 940 kg pig iron per tonne liquid steel and 1160 kg sinter per tonne pig iron. Based on these conversion factors the average CO_2 emissions from the four European sinter plants is 0.2 kg CO_2 per kg sinter produced.

The CO_2 emission factor for blast furnace iron making is derived by averaging plant-specific CO_2 emissions data for European sinter plants reported in the IPPC I&S BAT Document. The CO_2 and CO content of blast furnace gas produced by the iron making process is reported in Tables 7.2 and 7.3 of the IPPC I&S BAT Document in units of kilograms of CO_2 per tonne of pig iron produced and kilograms of CO per tonne of pig iron produced. The CO_2 content ranges from 400 to 900 kg CO_2 per tonne pig iron produced and the CO content ranges from 300 to 700 kg CO per tonne of pig iron produced. Based on the assumption that all of the blast furnace gas burned for energy recovery (and combusted to CO_2) within the integrated iron and steel mill and that no blast furnace gas is transferred off site, this corresponds to an emission factor of 1.35 kg CO_2 per kg pig iron produced.

TABLE 4.1
TIER 1 DEFAULT CO_2 EMISSION FACTORS FOR COKE PRODUCTION AND IRON & STEEL PRODUCTION

Process	Emission Factor	Source
Sinter Production (tonne CO_2 per tonne sinter produced)	0.20	Sinter 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 4.1, Page 29. http://eippcb.jrc.es/pages/FActivities.htm
Coke Oven (tonne CO_2 per tonne coke produced)	0.56	Coke 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 6.2, Page 122. http://eippcb.jrc.es/pages/FActivities.htm
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
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)
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)

* 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.

** 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.

Note that the CO_2 emission factor for EAF steelmaking in this table is based on production of steel from scrap metal, and therefore the EAF emission factor does not account for any CO_2 emissions from blast furnace iron making. The Tier 1 CO_2 emission factor for EAFs in this table is therefore not applicable to EAFs that use pig iron as a raw material.

The emission factor for pellet production is based on the IPPC I&S BAT Document which provides an emission factor range of 15.6 to 31.8 kg CO_2 per tonne product. However, the CO_2 emission factor for a specific process will depend on the characteristic of the raw materials and fuels used in the process. The emission factor would vary depending upon whether coal, natural gas, or coke oven gas was used as the primary fuel. The 'default' emission factor provided is at the high end of the range, 30 kg CO_2 per tonne product, and should be used if the inventory compiler does not know anything about the fuels or raw materials used. If the inventory compiler knows the inputs used, CO_2 emissions should be calculated using the Tier 2 method, accounting for the fuel consumption, heating value and carbon content of the fuel.

For the purposes of Tier 1 emission calculations, it is assumed that the default fuel for production of Direct Reduced Iron is natural gas. Natural gas-based processes account for the vast majority of installed direct reduced iron (DRI) production capacity worldwide, with 63 percent of that capacity being the MIDREX process. Fuel consumption for production of direct reduced iron using the MIDREX process is typically 10.5 - 14.5 GJ natural gas/metric tonne solid DRI assuming 100 percent lump iron ore operation. Fuel consumption for production of hot briquetted iron from iron fines was reported to be 12.5 GJ natural gas per tonne of product for the FINMET process and 14 GJ natural gas per tonne of product for the CIRCORED process. The default energy consumption of 12.5 GJ natural gas per tonne of DRI produced and the default carbon content of natural gas of 15.3 kg carbon per GJ natural gas correspond to a CO_2 emission factor of 191.3 kg carbon per tonne DRI produced (0.7 tonnes CO_2 per tonne DRI produced).

Methane emission factors

Default CH_4 emission factors are provided in Table 4.2 below. The Tier 1 CH_4 emission factor for coke production is derived by averaging plant-specific CH_4 emissions data for 11 European coke plants reported in the IPPC I&S BAT Document. Emissions of CH_4 are reported in Table 6.2 and Table 6.3 of the IPPC I&S BAT Document in units of grams of CH_4 per tonne of liquid steel produced. The CH_4 emissions reported range from 27 to 32 grams CH_4 per tonne liquid steel. Based on the conversion factors the average CH_4 emissions from the 11 European coke plants is 0.1 grams CH_4 per tonne coke produced.

The Tier 1 CH_4 emission factor for sinter production is derived by averaging plant-specific CH_4 emissions data for European sinter plants reported in the EMEP/CORINAIR Emissions Inventory Guidebook (EEA, 2005) and in other emission inventory reports. Emissions of CH_4 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 CH_4 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 CH_4 per tonne sinter using the default value of 28.2 TJ/Gg coke. An emission factor of 0.05 kg CH_4 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	0.1 g per tonne of coke produced	Coke 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 6.2-3, Page 122. http://eippcb.jrc.es/pages/FActivities.htm
Sinter Production	0.07 kg per tonne of sinter produced	EMEP/CORINAIR Emission Inventory Guidebook (EEA, 2005). Processes With Contact: *Sinter and Pelletizing Plants: Sinter and Pelletizing Plants (Except Combustion 030301)* Table 8.2a Emission factors for gaseous compounds
DRI Production	1 kg /TJ (on a net calorific basis)	Energy Volume default emission factor for CH_4 Emissions from natural gas combustion. [See Table 2.3 of Volume 2, Chapter 2.]

TIER 2 METHOD

The default carbon contents in Table 4.3 should be used if an inventory compiler does not have information on conditions in iron and steel-making facilities and coke production facilities, but has detailed activity data for the process materials and offsite transfers. The Tier 2 method, as described in Equation 4.2 for integrated coke production, Equations 4.9 to 4.11 for iron and steel production and Equation 4.3 for non-integrated coke production includes the major material flows in iron and steel-making and coke production that lead to emissions. Carbon contents in Table 4.3 are based on those provided in Table 1.2 and 1.3 in Volume 2, Chapter 1.

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	0.17
Charcoal*	0.91
Coal[1]	0.67
Coal Tar	0.62
Coke	0.83
Coke Oven Gas	0.47
Coking Coal	0.73
Direct Reduced Iron (DRI)	0.02
Dolomite	0.13
EAF Carbon Electrodes[2]	0.82
EAF Charge Carbon[3]	0.83
Fuel Oil[4]	0.86
Gas Coke	0.83
Hot Briquetted Iron	0.02
Limestone	0.12
Natural Gas	0.73
Oxygen Steel Furnace Gas	0.35
Petroleum Coke	0.87
Purchased Pig Iron	0.04
Scrap Iron	0.04
Steel	0.01

Source: Default values are consistent with the those provided in Vol 2 and have been calculated with the assumptions below. Complete references for carbon content data are included in Table 1.2 and 1.3 in Volume 2, Chapter 1.

Notes:

[1] Assumed other bituminous coal

[2] Assumed 80 percent petroleum coke and 20 percent coal tar

[3] Assumed coke oven coke

[4] Assumed gas/diesel fuel

* 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.)

TIER 3 METHODS

The Tier 3 method is based on aggregated plant-specific emission estimates or the application of the Tier 2 equations 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 Table 4.3 provides default carbon contents, it is *good practice* under Tier 3 to adjust these values to reflect variations at the plant level from default values represented in the table. 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.

4.2.2.4 CHOICE OF ACTIVITY DATA

TIER 1 METHOD

The Tier 1 method requires only the amount of steel produced in the country by process type, the total amount of pig iron produced that is not processed into steel, and the total amount of coke, direct reduced iron, pellets, and sinter produced; in this case the total amount of coke produced is assume to be produced in integrated coke production facilities. These data may be available from governmental agencies responsible for manufacturing statistics, business or industry trade associations, or individual iron and steel companies. If a country only has aggregate data available, a weighted factor should be used. Total crude steel production is defined as the total output of usable ingots, continuously-cast semi-finished products, and liquid steel for castings.

TIER 2 METHOD

The Tier 2 method requires the total amount of iron and steel, coke oven gas, blast furnace gas, and process materials such as limestone used for iron and steel production, direct reduced iron production, and sinter production in the country, in addition to onsite and offsite production of coke. These data may be available from governmental agencies responsible for manufacturing or energy statistics, business or industry trade associations, or individual iron and steel companies. These amounts can then be multiplied by the appropriate default carbon contents in Table 4.3 and summed to determine total CO_2 emission from the sector. However, activity data collected at the plant-level is preferred (Tier 3). If this is not a *key category* and data for total industry-wide reducing agents and process materials are not available, emissions can be estimated using the Tier 1 approach.

TIER 3 METHOD

The Tier 3 method requires collection, compilation, and aggregation of facility-specific measured emissions data or facility-specific process material production/consumption mass data and carbon content data The Tier 3 method can be based on a plant-specific mass balance approach (for CO_2 emissions) or on plant-specific direct emissions monitoring data (for both CO_2 and CH_4 emissions) . The Tier 3 method also may require activity data to be collected at the plant level and aggregated for the sectors. The plant-specific data should preferably be aggregated from data furnished by individual iron and steel and coke production companies. The amounts of process materials are more accurately determined in this manner. These data may also be available from governmental agencies responsible for manufacturing or energy statistics, or from business or industry trade associations. The appropriate amounts can then be multiplied by facility specific carbon content data and summed to determine total CO_2 emissions from the sectors, and the total emissions will be more accurate than when using the Tier 2 method. This approach also allows for additional accuracy by allowing individual companies to provide more accurate plant-specific data and/or to use more relevant carbon contents that may differ from the default factors used in Tier 2 method.

4.2.2.5 COMPLETENESS

RELATIONSHIP TO THE ENERGY SECTOR

In estimating emissions from this source category: coke production (Energy) and iron and steel production (IPPU), there is a risk of double counting or omission in either the Industrial Processes or the Energy Sector. Since the primary use of carbon sources (predominantly coke, but also coal, oil, natural gas, limestone, etc.) is to produce pig iron, the CO_2 and CH_4 emissions from iron and steel production including sinter production are considered industrial process emissions and should be reported as such. The CO_2 and CH_4 emissions from coke production (both fuel consumption and conversion losses) are categorised as energy production and should be reported as such. However, for integrated production and iron and steel with onsite coke production, there may be flows of by-products (e.g., coke oven gas, blast furnace gas, coke oven by-products) between the coke production facility and the iron and steel production facility, creating potential double counting issues. Carbon consumed in the from of coke oven gas at an iron and steelmaking facility and the resulting CO_2 and CH_4 emissions would be categorized as IPPU emissions and reported as such. Carbon consumed in the form of blast furnace gas at an onsite coke production facility and the resulting CO_2 and CH_4 emissions would be categorized as Energy emissions and should reported as such Tracking of such carbon flows will require good knowledge of the inventory in that source category.

Because of the dominant role of coke, it is important to consider the existence of coke making at a facility and define the boundary limits of a carbon balance at an iron and steelmaking facility to assure that CO_2 emissions are not double-counted. CO_2 and CH_4 emissions associated with onsite and offsite coke making are to be reported under Energy Sector (see Volume 2).

OTHER FORMS OF CARBON

Although the dominant means of producing crude iron, or pig iron, is the blast furnace using coke, other forms of carbon (e.g., pulverized coal, coal derivatives, recycled plastics or tires, natural gas, or fuel oil) can also be used to substitute for some portion of the coke in the blast furnace. In these cases, these materials should be accounted for as process sources of carbon in the same manner as coke, and care should be taken to deduct these materials from any general energy statistics if they are included there. Iron can also be produced in other types of iron making vessels besides blast furnaces, often using natural gas or coal instead of coke, and these carbon sources should be accounted for in the same manner as coke because they are serving the same purpose.

In most blast furnaces, the iron making process is aided by the use of carbonate fluxes (limestone or dolomite). Because these materials are necessary raw materials for the process, they should be accounted for as part of the iron and steelmaking inventory. Again, however, care should be taken not to double-count emissions associated with limestone and dolomite usage if accounted for separately in the minerals sector. (See Section 2.5, Other Process Uses of Carbonates, in this volume.)

SINTER

Some integrated facilities also utilize sinter plants to convert iron-bearing fines into an agglomerate (or sinter) suitable for use as a raw material in the blast furnace. Typically, coke fines (or coke breeze) are used as a fuel in the sintering process and are a source of CO_2 and CH_4 emissions. If the coke fines are produced at a coke plant within the facility and the CO_2 and CH_4 emissions are accounted for in the coal entering the facility, or if the coke breeze is otherwise accounted for as purchased coke, the CO_2 and CH_4 emissions from coke used in sintering should not be double-counted. Emissions from sinter production are categorised as IPPU emissions and should be reported as such.

EXHAUST GASES

It is important 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 CO_2, 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.

ELECTRODE CONSUMPTION

Electrode consumption amounts to about 3.5 kg/tonne for EAF furnaces. However, depending upon the characteristics of the charged materials, some carbon may be added to the EAF (typically about 20 kg/tonne) for process control purposes or may be contained in the charged materials themselves as iron substitutes, an increasingly more frequent trend. In these cases, CO_2 and CH_4 emissions from these additional carbon-bearing materials should be considered process-related and accounted for in the inventory because their carbon content is not as likely to have been accounted for elsewhere in the inventory. In addition, if natural gas is used to enhance reactions in an EAF as reducing agent it should be accounted for as a carbon source as all process materials used in iron and steel manufacturing are reported as IPPU emissions.

Some specialty steel production takes place in electric induction furnaces, in which case the charge is 100 percent steel scrap and where there are no carbon electrodes. There are no appreciable CO_2 or CH_4 emissions from this steelmaking process.

OHF PROCESS

Although the OHF is no longer prevalent, it may be necessary to inventory CO_2 and CH_4 emissions from this steelmaking process in some countries. An open hearth furnace is typically charged with both molten iron and scrap as in the case of a BOF, and oxygen is injected into the furnace, but reduction of carbon in the iron and melting of the charge also takes place by firing fossil fuels (e.g., natural gas, fuel oil, coal or tar) across the surface of the raw material bath. Carbon in the iron may be ignored, as in the case of the BOF, because it has been accounted for as a source of carbon for iron-making. However, carbon in the fuels used in the open hearth process should be accounted for as IPPU emissions.

4.2.2.6 DEVELOPING A CONSISTENT TIME SERIES

Emissions from coke production, sinter production, and iron and steel and production should be calculated using the same method for every year in the time series. Where data are unavailable to support a more rigorous method for all years in the time series, these gaps should be recalculated according to the guidance provided in Volume 1, Chapter 5, Time Series Consistency and Recalculation.

4.2.3 Uncertainty assessment

The default emission factors for coke production and iron and steel production used in Tier 1 may have an uncertainty of ± 25 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	± 25%
	National Production Data	± 10%
Tier 2	Material-Specific Default Carbon Contents	± 10%
	National Reducing Agent & Process Materials Data	± 10%
Tier 3	Company-Derived = Process Materials Data	± 5%
	Company-Specific Measured CO_2 and CH_4 Data	± 5%
	Company-Specific Emission Factors	± 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

4.2.4.1 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Volume 1, Chapter 6, and an expert review of the emissions estimates. Additional quality control checks as outlined in Volume 1, Chapter 6, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventories agencies are encouraged to use higher tier QA/QC for *key categories* as identified in Volume 1, Chapter 4.

In addition to the guidance in Volume 1, specific procedures of relevance to this source category are outlined below.

Review of emission factors and carbon contents

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

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.

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 is in place at most sites, then the uncertainty of the emissions estimates may be revised downwards.

Expert review

Inventory compilers should include key industrial trade organisations associated with iron and steel production in a review process. This process should begin early in the inventory development process to provide input to the development and review of methods and data acquisition

Third party reviews are also useful for this source category, particularly related to initial data collection, measurement work, transcription, calculation and documentation.

Activity data check

For all tier levels, inventory compilers should check with Volume 2, Chapter 2 (Stationary Combustion of Energy Sector) to ensure that emissions from reducing agents and process materials (coal, coke, natural gas, etc.) are not double-counted or omitted.

Inventory compilers should examine any inconsistency between data from different plants to establish whether these reflect errors, different measurement techniques or result from real differences in emissions, operational conditions or technology. This is particularly relevant to the plant-specific estimates of amounts of reducing agents or reported carbon content of process materials.

Inventory compilers should compare aggregated plant-level estimates to industry totals for process materials consumption where such trade data are available.

4.2.4.2 REPORTING AND DOCUMENTATION

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

TIER 1 METHOD

Besides reporting of estimated emissions, it is *good practice* to report the total steel production by process and corresponding emission factors used and to report the amount of iron produced that is not processed into steel. In the corresponding table, it should be noted that reported emissions are only part of total emissions from the sector and that coke production emissions are categorized as energy emissions and are reported in Volume 2, Chapter 2, Stationary Combustion of Energy Sector.

TIER 2 METHODS

Good practice is to document the estimated or calculated emissions, all activity data, and corresponding emission factors and any assumptions or data justifying alternative emission factors. There should be a clear explanation of the linkage with the source category 1A (Fuel Combustion) estimate for integrated coke production emissions to demonstrate that double counting or missing emissions have not occurred.

TIER 3 METHOD

Good practice is to document the calculated emissions and source of all data, taking into account the need to protect the confidentiality of data for specific facilities if the data are business-sensitive or of a proprietary nature. In addition, inventory compilers should for all tiers, document all information needed to reproduce the estimate, as well as the QA/QC procedures.

4.3 FERROALLOY PRODUCTION

4.3.1 Introduction

Ferroalloy is the term used to describe concentrated alloys of iron and one or more metals such as silicon, manganese, chromium, molybdenum, vanadium and tungsten. Silicon metal production is usually included in the ferroalloy group because silicon metal production process is quite similar to the ferrosilicon process. These alloys are used for deoxidising and altering the material properties of steel. Ferroalloy facilities manufacture concentrated compounds that are delivered to steel production plants to be incorporated in alloy steels. Silicon metal is used in aluminium alloys, for production of silicones and in electronics. Ferroalloy production involves a metallurgical reduction process that results in significant carbon dioxide emissions.

In ferroalloy production, raw ore, carbon materials and slag forming materials are mixed and heated to high temperatures for reduction and smelting. The carbonaceous reductants are usually coal and coke, but bio-carbon (charcoal and wood) is also commonly used as a primary or secondary carbon source. Carbon dioxide (CO_2) and methane (CH_4) emissions from coke production are estimated in Section 4.2 and reported within the Energy Sector. Electric submerged arc furnaces with graphite electrodes or consumable Søderberg electrodes are used. The heat is produced by the electric arcs and by the resistance in the charge materials. The furnaces may be open, semi-covered or covered. A commonly used technology is the submerged-arc open-top electric furnace (EAF). In the EAF, passing current through graphite electrodes suspended in a cup-shaped, refractory-lined steel shell accomplishes heating. Carbon reduction of the metallic oxides occurs as both coke and graphite electrodes are consumed. The carbon in the electrodes captures the oxygen from the metal oxides to form CO, while the ores are reduced to molten base metals. The component metals then combine in the solution.

In addition to emissions originating from reducing agents and electrodes, the calcination of carbonate fluxes such as limestone or dolomite, when used, contribute to the emission of greenhouse gases.

Primary emissions in covered arc furnaces consist almost entirely of CO as opposed to CO_2, due to the strong reducing environment. This CO is either utilised for energy production in boilers, or it is flared. The energy produced is assumed to be used internally at the site and the carbon content of the CO subsequently converted to CO_2 in-plant.

The CO gas produced in open or semi-closed furnaces is burnt to CO_2 above the charge level. Any CO emitted to the atmosphere is assumed to be converted to CO_2 within days afterwards. While CO_2 is the main greenhouse gas from ferroalloy production, recent research has shown that CH_4, and N_2O account for an equivalent greenhouse emission of up to 5 percent of the CO_2 emissions from ferrosilicon (FeSi) and silicon-metal (Si-metal) production. Methodologies are presented for CO_2 and CH_4 emissions in this section. These emissions should be better investigated for all ferroalloy production, and more measurements of these emissions should be done from FeSi and Si-metal production.

4.3.2 Methodological issues

4.3.2.1 CHOICE OF METHOD

METHODOLOGY FOR CO_2

The *IPCC Guidelines* outline several approaches for calculating CO_2 emissions from ferroalloy production. For practical purposes, this section adopts a mass balance approach where all CO emitted is reported as emitted CO_2. The choice of a *good practice* method depends on national circumstances as shown in the decision tree in Figure 4.9. The Tier 1 method calculates emissions from general emission factors applied to a country's total ferroalloy production. The Tier 1 method is very simple, and it may lead to errors due to its reliance on assumptions rather than actual data. Therefore it is appropriate only when ferroalloy production is not a *key category*. The Tier 2 method calculates emissions from a known consumption of reducing agents, preferably from plant-specific consumption data, but alternatively from industry-wide data using emission factors similar to those used to estimate combustion emissions. The Tier 3 method is based on facility-specific emissions data.

Tier 1 method: production-based emission factors

The simplest estimation method is to multiply default emission factors by ferroalloy product type as shown in Equation 4.15.

EQUATION 4.15
CO_2 EMISSIONS FOR FERROALLOY PRODUCTION BY THE TIER 1 METHOD

$$E_{CO2} = \sum_i \left(MP_i \bullet EF_i \right)$$

Where:

E_{CO2} = CO_2 emissions, tonnes

MP_i = production of ferroalloy type *i*, tonnes

EF_i = generic emission factor for ferroalloy type *i*, tonnes CO_2/tonne specific ferroalloy product

Tier 2 method: production-based, raw material specific emission factors

An alternate approach is to use emission factors for the reducing agents. For the other raw materials and products carbon contents should be considered.

BOX 4.1
DEFINITIONS FOR WORDS/SYMBOLS USED IN EQUATIONS IN THIS SECTION

Content means weight-fraction in all equations

$\sum$ means the sum of all *i*, *h*, *j*, *k* or *l*

EQUATION 4.16
CO_2 EMISSIONS FOR FERROALLOY PRODUCTION BY TIER 2 METHOD

$$\begin{aligned} E_{CO2} = & \sum_i \left(M_{reducing\ agent,i} \bullet EF_{reducing\ agent,i} \right) + \sum_h \left(M_{ore,h} \bullet CContent_{ore,h} \right) \bullet \frac{44}{12} \\ & + \sum_j \left(M_{slag\ forming\ material,j} \bullet CContent_{slag\ forming\ material,j} \right) \bullet \frac{44}{12} \\ & - \sum_k \left(M_{product,k} \bullet CContent_{product,k} \right) \bullet \frac{44}{12} \\ & - \sum_l \left(M_{non-product\ outgoing\ stream,l} \bullet CContent_{non-product\ outgoing\ stream,l} \right) \bullet \frac{44}{12} \end{aligned}$$

Where:

ECO_2 = CO_2 emissions frm ferroalloy production, tonnes

$M_{\text{reducing agent, i}}$ = mass of reducing agent *i*, tonnes

$EF_{\text{reducing agent, i}}$ = emission factor of reducing agent *i*, tonnes CO_2/tonne reducing agent

$M_{\text{ore, h}}$ = mass of ore *h*, tonnes

$CContent_{\text{ore, h}}$ = carbon content in ore *h*, tonnes C/tonne ore

$M_{\text{slag forming material, j}}$ = mass of slag forming material *j*, tonnes

$CContent_{\text{slag forming material, j}}$ = carbon content in slag forming material *j*, tonnes C/tonne material

$M_{\text{product, k}}$ = mass of product *k*, tonnes

$CContent_{\text{product, k}}$ = carbon content in product *k*, tonnes C/tonne product

$M_{\text{non-product outgoing stream, l}}$ = mass of non-product outgoing stream *l*, tonnes

$CContent_{\text{non-product outgoing stream, l}}$ = carbon content in non-product outgoing stream *l*, tonnes C/tonne

The constant 44/12 is the multiplication factor for the mass of CO_2 emitted from each mass unit of total carbon used.

Tier 3 method: calculations based on amounts and analyses of reducing agents

The producers use coal and coke with different contents of ash, fixed carbon and volatiles. Further, the amounts of carbon in carbonate ores and slag forming materials will vary. The most accurate method is therefore to calculate the CO_2 emissions from the total amount of carbon in reducing agents, electrode paste, ores, slag forming materials and products, and this calculation is carried out for each ferroalloy produced.

EQUATION 4.17

CO_2 EMISSIONS FOR FERROALLOY PRODUCTIION BY TIER 3 METHOD

$$
\begin{aligned}
E_{CO2} = & \sum_i \left(M_{reducing\ agent,i} \bullet CContent_{reducing\ agent,i} \right) \bullet \frac{44}{12} \\
& + \sum_h \left(M_{ore,h} \bullet CContent_{ore,h} \right) \bullet \frac{44}{12} \\
& + \sum_j \left(M_{slag\ forming\ material,j} \bullet CContent_{slag\ forming\ material,j} \right) \bullet \frac{44}{12} \\
& - \sum_k \left(M_{product,k} \bullet CContent_{product,k} \right) \bullet \frac{44}{12} \\
& - \sum_l \left(M_{non-product\ outgoing\ stream,l} \bullet CContent_{non-product\ outgoing\ stream,l} \right) \bullet \frac{44}{12}
\end{aligned}
$$

Where:

ECO_2 = CO_2 emissions frm ferroalloy production, tonnes

$M_{\text{reducing agent, i}}$ = mass of reducing agent *i*, tonnes

$CContent_{\text{reducing agent, i}}$ = carbon content in reducing agent *i*, tonnes C/tonne reducing agent

$M_{\text{ore, h}}$ = mass of ore *h*, tonnes

$CContent_{\text{ore, h}}$ = carbon content in ore *h*, tonnes C/tonne ore

$M_{\text{slag forming material, j}}$ = mass of slag forming material *j*, tonnes

$CContent_{\text{slag forming material, j}}$ = carbon content in slag forming material *j*, tonnes C/tonne material

$M_{\text{product, k}}$ = mass of product *k*, tonnes

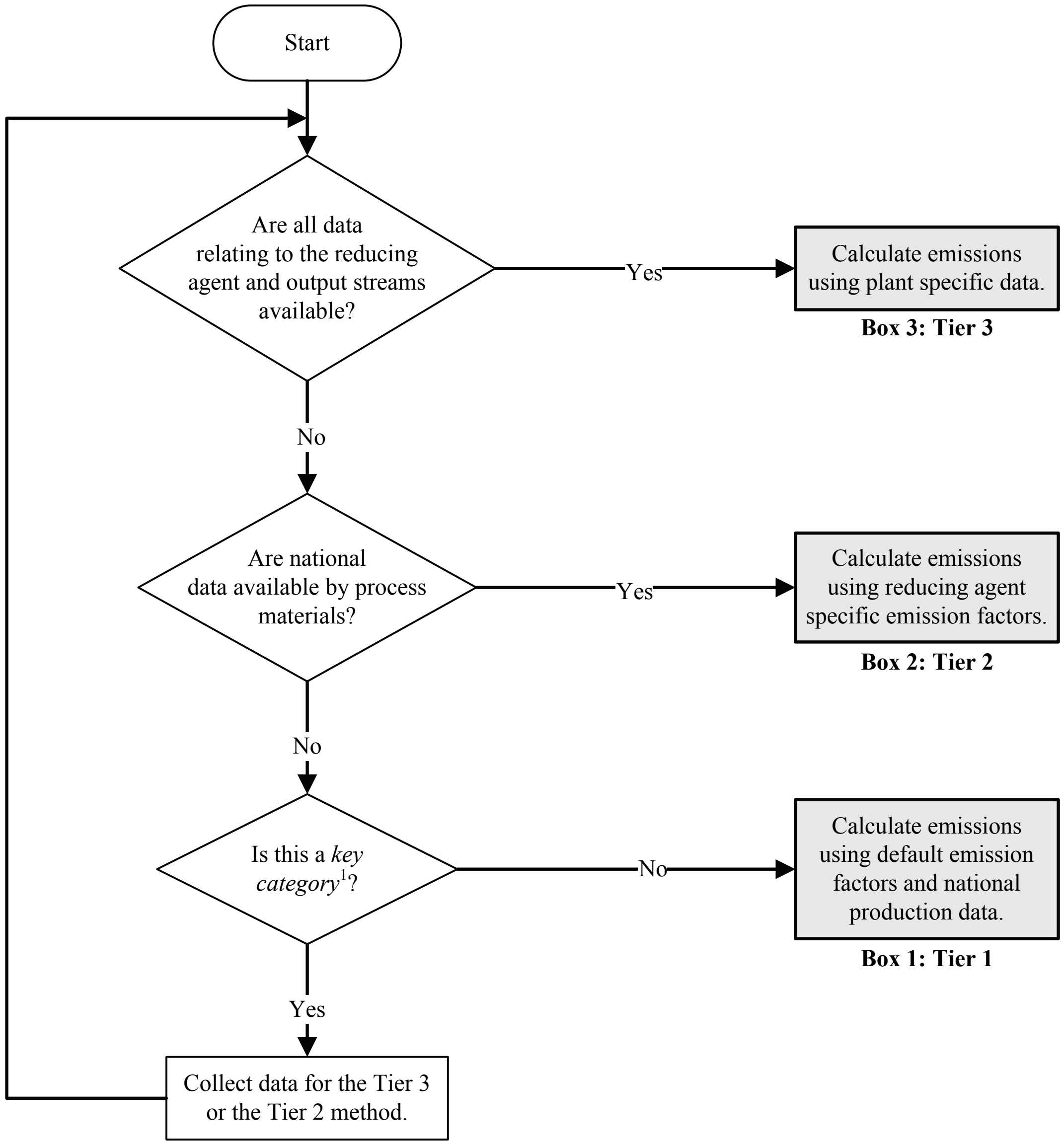
$CContent_{\text{product, k}}$ = carbon content in product *k*, tonnes C/tonne product

$M_{\text{non-product outgoing stream, l}}$ = mass of non-product outgoing stream *l*, tonnes

$CContent_{\text{non-product outgoing stream, l}}$ = carbon content in non-product outgoing stream *l*, tonnes C/tonne

The constant 44/12 is the multiplication factor for the mass of CO_2 emitted from each mass unit of total carbon used. The calculation will have good accuracy if analyses of total carbon in all reducing agents are available.

Figure 4.9 Decision tree for estimation of CO_2 emissions from ferroalloy 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.

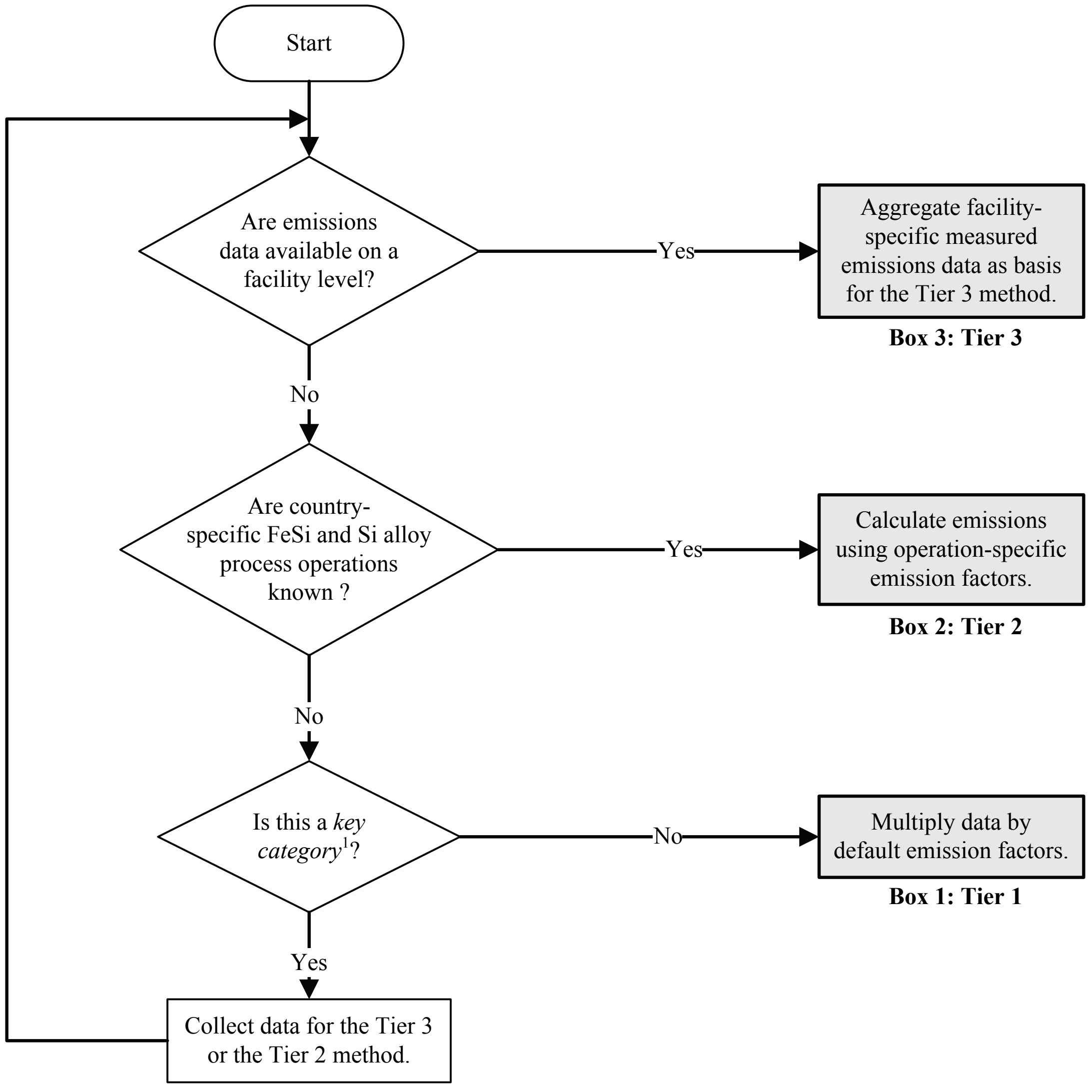
METHODOLOGY FOR CH_4 AND DISCUSSION OF N_2O EMISSIONS

The heating of carbon materials in the furnace releases volatiles including methane. With open or semi-covered furnaces – predominantly used for FeSi and Si ferroalloy production - most of the volatiles will burn to CO_2 above the charge, in the hood and off-gas channels, but some will remain un-reacted as CH_4 and NMVOC. The amounts depend on the operation of the furnace. Sprinkle-charging will reduce the amounts of CH_4 compared to batch-wise charging. Increased temperature in the hood (less false air) will reduce the content of CH_4 further.

The *IPCC Guidelines* outline several approaches for calculating CH_4 emissions from FeSi- and Si- ferroalloy production. The choice of a *good practice* method depends on national circumstances as shown in the decision tree in Figure 4.10. The Tier 1 method calculates emissions from general emission factors applied to a country's total ferroalloy production. The Tier 1 method is very simple, and it may lead to errors due to its reliance on assumptions rather than actual data. Therefore it should only be used when ferroalloy production is not a *key category*. The Tier 2 method calculates emissions from operation-specific emission factors. The Tier 3 method uses facility-specific emissions data.

The errors associated with estimates or measurements of N_2O emissions from the ferroalloys industry are very large and thus, a methodology is not provided.

Figure 4.10 Decision tree for estimation of CH_4 emissions from FeSi and Si alloy 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 1 method: FeSi and Si alloy production-based emission factors

The simplest estimation method is to multiply default emission factors by Si-alloy product type.

Total emissions are calculated according to:

EQUATION 4.18

CH_4 EMISSIONS FOR FERROALLOY PRODUCTION BY THE TIER 1 METHOD

$$E_{CH4} = \sum_i \left(MP_i \bullet EF_i\right)$$

Where:

E_{CH4} = CH_4 emissions, kg

MP_i = production of Si-alloy *i*, tonnes

EF_i = generic emission factor for Si-alloy *i*, kg CH_4/ tonne specific Si-alloy product

Tier 2 method: FeSi and Si alloy production-based, operation specific emission factors

The Tier 2 method is also based on emission factors but unlike the Tier 1 method, these are operation specific.

Tier 3 method: Direct measurements

Inventory compilers are strongly encouraged to measure CH_4 emissions where emissions from ferroalloys industry is a *key category*.

4.3.2.2 CHOICE OF EMISSION FACTORS

EMISSION FACTORS FOR CO_2

Tier 1 method: production-based emission factors

When the only data available are national ferroalloy production statistics, it is *good practice* to use default emission factors. However, because of widely disparate factors depending on the type of ferroalloy production, it is necessary to determine how much tonnage is produced by which method and then to sum the product of the factors shown in Table 4.5 and the appropriate production tonnages. These factors are based on expert judgement using typical practice for the ferroalloy production scenarios listed. If any bio-carbon, except some woodchips for FeSi and Si-metal production, is used, the factors cannot be employed.

TABLE 4.5
GENERIC CO_2 EMISSION FACTORS FOR FERROALLOY PRODUCTION
(tonnes CO_2/tonne product)

Type of Ferroalloy	Emission Factor
Ferrosilicon 45% Si	2.5
Ferrosilicon 65 % Si	3.6
Ferrosillicon 75% Si	4.0
Ferrosillicon 90% Si	4.8
Ferromanganeses (7% C)	1.3
Ferromanganeses (1% C)	1.5
Silicomanganese	1.4
Silicon metal	5.0
Ferrochromium	1.3 (1.6 with sinter plant)

Source: IPCC (1997), IPCC (2000), Olsen (2004) and Lindstad (2004)

These default emission factors have been assessed by Olsen (2004) for the manganese alloys, Lindstad (2004) for the silicon alloys and by Olsen, Monsen and Lindstad (1998) for FeCr.

For FeMn alloys the emission factors are based on production where the Mn containing raw materials are a mixture of oxide ores, carbonate ores and imported Mn-sinter. If the sinter is produced abroad it will not give any contribution to the national greenhouse gas inventory. Emission from sinter production must be reported where the production is located.

The factor for FeSi90 and Si-metal is based on a Fix C consumption of 110 percent of the stoichiometric amount needed for reduction of SiO_2. For the other FeSi-alloys the factor is based on 114 percent of the stoichiometric amount of Fix C.

Tier 2 method: production-based, raw material specific emission factors

The emission factors for the reducing agents used in production of manganese and silicon alloys are given in Table 4.6. The factors have been assessed by Olsen (2004) for use in manganese alloys production and by Lindstad (2004) for use in silicon alloys.

TABLE 4.6
CO_2 EMISSION FACTORS FOR FERROALLOY PRODUCTION
(tonnes CO_2/tonne reducing agent)

Reducing agent (usage)	Emission Factor
Coal (for FeSi and Si-metal)	3.1
Coal (for other ferroalloys)	* (See below)
Coke (for FeMn and SiMn)	3.2-3.3
Coke (for Si and FeSi)	3.3-3.4
Coke (for other ferroalloys)	* (See below)
Prebaked electrodes	3.54
Electrode paste	3.4
Petroleum coke	3.5

*: Inventory compilers are encouraged to use producer-specific values based on average blend of coal and/or coke for each ferroalloy producer.

Source: Olsen (2004), Lindstad (2004)

Tier 3 method: calculations based on amounts and analyses of reducing agents

For the Tier 3 method, it is necessary to determine the carbon contents of the reducing agents used in the production processes. But most ferroalloys producers analyse only on the basis of percentage of ash and volatiles, and calculate:

Fix C % = 100 % – % Ash – % Volatiles.

In that case, the total C-contents of reducing agents. is calculated by the following equation.

EQUATION 4.19
CARBON CONTENTS OF FERROALLOY REDUCTING AGENTS

$$CContent_{reducing\ agent,i} = F_{FixC,i} + F_{volatiles,i} \bullet C_v$$

Where:

$CContent_{reducing\ agent,\ i}$ = carbon content in reducing agent *i*, tonnes C/tonne reducing agent

$F_{FixC,i}$ = mass fraction of Fix C in reducing agent *i*, tonnes C/ tonne reducing agent

$F_{volatiles,i}$ = mass fraction of volatiles in reducing agent *i*, tonnes volatiles/ tonne reducing agent

C_v = carbon content in volatiles, tonnes C/tonne volatiles
(Unless other information is available, Cv = 0.65 is used for coal and 0.80 for coke.)

EMISSION FACTORS FOR CH_4

Tier 1 method: FeSi and Si alloy production-based emission factors

When the only data available are national ferroalloy production statistics, it is *good practice* to use default emission factors. However, because of the disparate factors depending on the type of ferroalloy production, it is necessary to determine how much tonnage is produced by which method and then to sum the product of the factors shown in Table 4.7 and the appropriate production tonnages. The default emission factors for CH_4 is based on the averages of a small number of operation-specific measurements (shown in Table 4.7 for Tier 2) carried out by SINTEF and DNV mainly in 1995 and 1998 (FFF (2000)).

TABLE 4.7
DEFAULT EMISSION FACTORS FOR CH_4 (kg CH_4/tonne product)

Emission	**Alloy**	**Emission Factor**
CH_4	Si-metal	1.2
	FeSi 90	1.1
	FeSi 75	1.0
	FeSi 65	1.0

Source: FFF (2000)

Tier 2 method: FeSi and Si alloy production-based, operation specific emission factors

The Tier 2 method is also based on emission factors but unlike the Tier 1 method, these factors are operation specific. The procedure is otherwise the same as that outlined in Equation 4.18, using values in Table 4.8.

TABLE 4.8
EMISSION FACTORS FOR CH_4 (kg CH_4/tonne product)

Emission	**Alloy**	**Operation of Furnace**		
		Batch-charging	**Sprinkle-charging $^{1)}$**	**Sprinkle-charging and >750^{0}C $^{2)}$**
CH_4	Si-metal	1.5	1.2	0.7
	FeSi 90	1.4	1.1	0.6
	FeSi 75	1.3	1.0	0.5
	FeSi 65	1.3	1.0	0.5

[1] Sprinkle-charging is charging intermittently every minute.

[2] Temperature in off-gas channel measured where the thermocouple cannot 'see' the combustion in the furnace hood.

Tier 3 method: Direct measurements

Tier 3 is based on measurements rather than emission factors. The inventory compiler should consult guidance on plant-level measurements outlined in Volume 1, Chapter 2, and on QA/QC of measurements in Volume 1, Chapter 6.

4.3.2.3 CHOICE OF ACTIVITY DATA

TIER 1 METHOD

The Tier 1 method requires only the amount of ferroalloy produced in the country by product type. These data may be available from governmental agencies responsible for manufacturing statistics, business or industry trade associations, or individual ferroalloy companies. These tonnages can then be multiplied by the corresponding emission factors in Table 4.5 to estimate CO_2 emissions from the sector and Table 4.7 to estimate CH_4 emissions from the sector.

TIER 2 METHOD

The Tier 2 method requires the total amount of reducing agent and other process materials used for ferroalloy production in the country, and knowledge of processes used. These data may be available from governmental agencies responsible for manufacturing or energy statistics, business or industry trade associations, or individual ferroalloy companies. These amounts can then be multiplied by the appropriate generic emission factors in Tables 4.6 and 4.8 and summed to determine total CO_2 and CH_4 emissions from the sector. However, activity data collected at the plant-level is preferred.

TIER 3 METHOD

The Tier 3 method requires collection, compilation, and aggregation of facility-specific emissions data. These data may be available directly from companies.

4.3.2.4 COMPLETENESS

In estimating emissions from this source category, there is a risk of double-counting or omission in either the Industrial Processes or the Energy Sector. Since the primary use of carbon sources (coal, coke, limestone, dolomite etc.) is to produce ferroalloys, the emissions are considered to be industrial process emissions and should be reported as such. It should be noted that the risk of double counting is particularly high for the Tier 1 approach. Any deviation from reporting emissions as originating from an industrial process should be explicitly mentioned in the inventory, and a double-counting/completeness check should be performed.

4.3.2.5 DEVELOPING A CONSISTENT TIME SERIES

Emissions from ferroalloy production should be calculated using the same method for every year in the time series. Where data are unavailable to support a Tier 3 method for all years in the time series, these gaps should be recalculated according to the guidance provided in Volume 1, Chapter 5.

4.3.3 Uncertainty assessment

Uncertainties for ferroalloy production result predominantly from uncertainties associated with activity data, and to a lesser extent from uncertainty related to the emission factor. Although some ferroalloys may be produced using wood or other biomass as a carbon source, information and data regarding these practices were not available. Emissions from ferroalloys produced with wood or other biomass would not be counted under this source because wood-based carbon is of biogenic origin. Emissions from ferroalloys produced with coking coal or graphite inputs would be counted in national trends, but may generate differing amounts of CO_2 per unit of ferroalloy produced compared to the use of petroleum coke.

4.3.3.1 EMISSION FACTOR UNCERTAINTIES

For Tier 3, actual emissions data would be expected to have less than 5 percent uncertainty. For Tier 2, the material-specific emission factors would be expected to be within 10 percent, which would provide less uncertainty overall than for Tier 1. Emission factors would be expected to be within 10 percent or less than 5 percent if plant-specific carbon content data are available. The default emission factors used in Tier 1 may have an uncertainty of 25 to 50 percent.

4.3.3.2 ACTIVITY DATA UNCERTAINTIES

For Tier 1 the most important type of activity data is the amount of ferroalloy production by product type. National statistics should be available and likely have an uncertainty less than 5 percent. Tier 2 applied with plant-specific information on the amounts of reducing agents and process materials as applied in Tier 2 method should not exceed 5 percent uncertainty.

TABLE 4.9
UNCERTAINTY RANGES

Method	Data Source	Unertainty Range
Tier 1	National Production Data Default Emission Factors	< 5% < 25 %
Tier 2	Company-Derived Reducing Agent & Process Materials National Reducing Agent & Process Materials Data Company-Specific Emission Factors Material-Specific Default Emission Factors	< 5% < 5% < 5% < 10%
Tier 3	Company-Specific Measured CO_2 Data	< 5%

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

4.3.4.1 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Volume 1, Chapter 6, and an expert review of the emissions estimates. Additional quality control checks as outlined in Volume 1, Chapter 6, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventories agencies are encouraged to use higher tier QA/QC for *key categories* as identified in Volume 1, Chapter 4.

In addition to the guidance in Volume 1, specific procedures of relevance to this source category are outlined below.

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.

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 ferroalloy production, inventory compilers should compare plant data with other plants.

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 is in place at most sites, then the uncertainty of the emissions estimates may be revised downwards.

Expert review

Inventory compilers should include key industrial trade organisations associated with ferroalloy production in a review process. This process should begin early in the inventory development process to provide input to the development and review of methods and data acquisition

Third party reviews are also useful for this source category, particularly related to initial data collection, measurement work, transcription, calculation and documentation.

Activity data check

For all tier levels, inventory compilers should check with Volume 2, Chapter 2, Stationary Combustion of Energy Sector, to ensure that emissions from reducing agents and process materials (coal, coke, natural gas, etc.) are not double-counted or omitted.

Inventory compilers should examine any inconsistency between data from different plants to establish whether these reflect errors, different measurement techniques or result from real differences in emissions, operational conditions or technology. This is particularly relevant to the plant-specific estimates of amounts of reducing agents or reported carbon content of process materials.

Inventory compilers should compare aggregated plant-level estimates to industry totals for process materials consumption where such trade data are available.

4.3.4.2 REPORTING AND DOCUMENTATION

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

TIER 1 METHOD

Besides reporting of estimated emissions, it is *good practice* to report the total ferroalloy production by process and corresponding emission factors used. In the corresponding table, it should be noted that reported emissions are only part of total emissions from the sector and the rest are reported elsewhere Volume 2, Chapter 2, Stationary Combustion of Energy Sector.

TIER 2 METHODS

Good practice is to document the estimated or calculated emissions, all activity data, and corresponding emission factors and any assumptions or data justifying alternative emission factors. There should be a clear explanation of the linkage with the Fuel Combustion Sub-Sector estimate to demonstrate that double counting or missing emissions have not occurred.

TIER 3 METHOD

Good practice is to document the calculated emissions and source of all data, taking into account the need to protect the confidentiality of data for specific facilities if the data are business-sensitive or of a proprietary nature. In addition, inventory compilers should for all tiers, document all information needed to reproduce the estimate, as well as the QA/QC procedures.

4.4 PRIMARY ALUMINIUM PRODUCTION

4.4.1 Introduction

This section covers process emissions from primary aluminium production[2]. Worldwide, primary aluminium is produced exclusively by the Hall-Heroult electrolytic process. In this process, electrolytic reduction cells differ in the form and configuration of the carbon anode and alumina feed system and belong to one of four technology types: Centre-Worked Prebake (CWPB)[3], Side-Worked Prebake (SWPB), Horizontal Stud Søderberg (HSS) and Vertical Stud Søderberg (VSS).

The most significant process emissions are:

(i) Carbon dioxide (CO_2) emissions from the consumption of carbon anodes in the reaction to convert aluminium oxide to aluminium metal;

(ii) Perfluorocarbons (PFCs) emissions of CF_4 and C_2F_6 during anode effects.

Also emitted are smaller amounts of process emissions, CO, SO_2, and NMVOC. SF_6 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[4].

The decision trees in Figures 4.11 and 4.12 provide guidance for selecting a methodology estimating 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 for both CO_2 and PFC emissions, 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

4.4.2.1 CHOICE OF METHOD FOR CO_2 EMISSIONS FROM PRIMARY ALUMINIUM PRODUCTION

During normal operations, aluminium is produced at the cathode and carbon is consumed at the anode per the electrolytic reduction reaction:

$$\boxed{2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2}$$

Most carbon dioxide emissions result from the electrolysis reaction of the carbon anode with alumina (Al_2O_3). The consumption of prebaked carbon anodes and Søderberg paste is the principal source of process related carbon dioxide emissions from primary aluminium production. Other sources of process related carbon dioxide emissions associated with Prebake anode baking account for less than 10 percent of the total non-energy related carbon dioxide emissions.

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

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[2] Emissions from the combustion of fossil fuels associated with primary aluminium production, bauxite mining, bauxite ore refining, and aluminium production from recycled sources are covered in Volume 2: Energy. Also, carbon dioxide emissions associated with production of electricity from fossil fuel combustion to produce aluminium are also covered in Volume 2.

[3] Including Point Feed Prebake and Bar Broken Prebake cells.

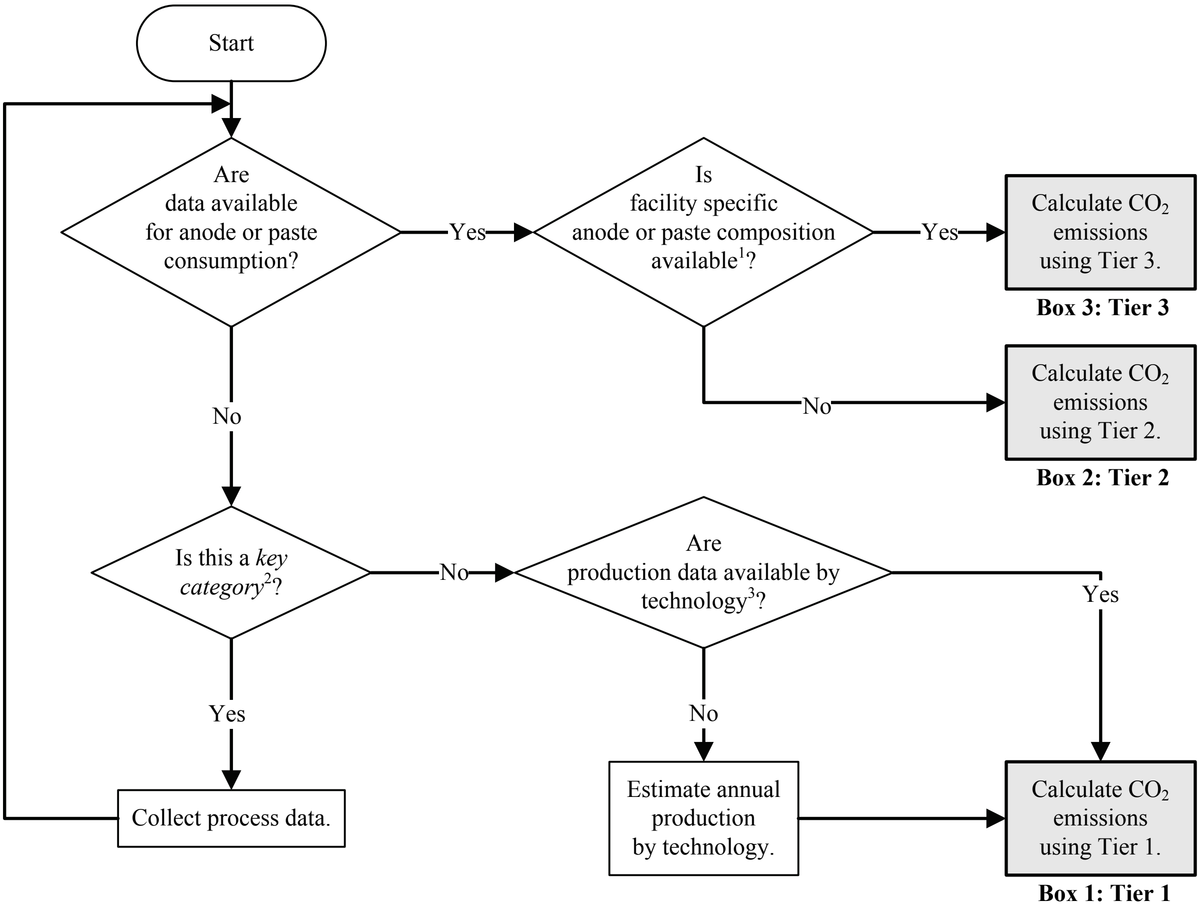
[4] A 2004 IAI survey found no evidence of SF_6 being emitted from primary aluminium smelting through the Hall-Heroult electrolytic production process.

producing carbon dioxide are included in process parameters routinely monitored at the production facilities, the net anode carbon consumed for Prebake facilities, or anode paste consumption for Søderberg facilities.

For the CO_2 emissions calculation, production data require technology differentiation as Søderberg or Prebake.There is no need for further differentiation as to the specific type of Søderberg or Prebake technology.

The decision tree shown in Figures 4.11 describes *good practice* in choosing the CO_2 inventory methodology appropriate for national circumstances.

Figure 4.11 Decision tree for calculation of CO_2 emissions from primary aluminium production



Note:

1. See International Aluminium Institute, The Aluminium Sector Greenhouse Gas Protocol, 2005.
2. See Volume 1 Chapter 4, Methodological Choice and Identification of Key Categories (noting Section 4.1.2 on limited resources), for discussion of *key categories* and use of decision trees.
3. For CO_2 emissions calculation, the production data requires technology differentiation as Søderberg or Prebake. There is no need for further differentiation as to the specific type of Søderberg or Prebake technology.

Tier 1 method for CO_2 emissions

The Tier 1 method for calculating CO_2 emissions uses only broad cell technology characterizations (Prebake or Søderberg) as a lower order estimate of CO_2 emissions from aluminium production. Given the uncertainty associated with the Tier 1 method, it is *good practice* to use higher tier methods if CO_2 from primary aluminium is a *key category*.

Total CO_2 emissions are calculated according to Equation 4.20.

EQUATION 4.20
PROCESS CO_2 EMISSIONS FROM ANODE AND/OR PASTE CONSUMPTION (TIER 1 METHOD)

$$E_{CO2} = EF_P \bullet MP_P + EF_S \bullet MP_S$$

Where:

E_{CO2} = CO_2 emissions from anode and/or paste consumption, tonnes CO_2

EF_P = Prebake technology specific emission factor (tonnes CO_2/tonne aluminium produced)

MP_P = metal production from Prebake process (tonnes Al)

EF_S = Søderberg technology specific emission factor (tonnes CO_2/tonne aluminium produced)

MP_S = metal production from Søderberg process (tonnes Al)

Tier 2 or Tier 3 methods for CO_2 emissions

For both the Prebake and Søderberg processes CO_2 emissions are calculated using a mass balance approach that assumes that the carbon content of net anode consumption or paste consumption is ultimately emitted as CO_2. The Tier 2 methods for both Prebake and Søderberg processes make use of typical industry values for impurities while the Tier 3 methods uses actual concentrations of impurities. The choice of method between the Tier 2 and Tier 3 method will depend on whether anode or paste composition data are available at the individual plant level.

CO_2 emissions for Prebake cells (CWPB and SWPB):

The CO_2 emissions for the Tier 2 and the Tier 3 method for Prebake cells are calculated according to Equation 4.21. Tier 3 requires specific operating facility data for all the components in Equation 4.21, whereas Tier 2 is based on default values for some of the components. Section 4.4.2.2 below provides more details on using these parameters.

EQUATION 4.21
CO_2 EMISSIONS FROM PREBAKED ANODE CONSUMPTION (TIER 2 AND TIER 3 METHODS)

$$E_{CO2} = NAC \bullet MP \bullet \frac{100 - S_a - Ash_a}{100} \bullet \frac{44}{12}$$

Where:

E_{CO2} = CO_2 emissions from prebaked anode consumption, tonnes CO_2

MP = total metal production, tonnes Al

NAC = net prebaked anode consumption per tonne of aluminium, tonnes C/ tonne Al

S_a = sulphur content in baked anodes, wt %

Ash_a = ash content in baked anodes, wt %

44/12 = CO_2 molecular mass: carbon atomic mass ratio, dimensionless

Equation 4.21 should be applied to each Prebake smelter in the country and the results summed to arrive at total national emissions. It is possible to use a hybrid Tier 2/3 approach if data on ash or sulphur content are not available for each smelter.

Emissions from the combustion of fossil fuels used in the production of baked anodes are covered in Volume 2: Energy. However, two other sources of CO_2 emissions are associated with anode baking furnaces – the combustion of volatile matter released during the baking operation and the combustion of baking furnace packing material (coke). Equations 4.22 and 4.23 can be used for the calculation of such emissions.[5]

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[5] For additional information on the application of these equations to estimate emissions from combustion of volatile matter, see the IAI Greenhouse Gas Protocol (IAI, 2005a).

EQUATION 4.22
CO_2 EMISSIONS FROM PITCH VOLATILES COMBUSTION (TIER 2 AND TIER 3 METHODS)

$$E_{CO2} = \left(GA - H_w - BA - WT\right) \bullet \frac{44}{12}$$

Where:

E_{CO2} = CO_2 emissions from pitch volatiles combustion, tonnes CO_2

GA = initial weight of green anodes, tonnes

H_w = hydrogen content in green anodes, tonnes

BA = baked anode production, tonnes

WT = waste tar collected, tonnes

EQUATION 4.23
CO_2 EMISSIONS FROM BAKE FURNACE PACKING MATERIAL (TIER 2 AND TIER 3 METHODS)

$$E_{CO2} = PCC \bullet BA \bullet \frac{100 - S_{pc} - Ash_{pc}}{100} \bullet \frac{44}{12}$$

Where:

E_{CO2} = CO_2 emissions from bake furnace packing material, tonnes CO_2

PCC = packing coke consumption, tonnes/tonne BA

BA = baked anode production, tonnes

S_{pc} = sulphur content in packing coke, wt %

Ash_{pc} = ash content in packing coke, wt %

CO_2 emissions for Søderberg cells (VSS and HSS):

The CO_2 emissions for the Tier 2 and the Tier 3 method for Søderberg cells are calculated according to Equation 4.24. Tier 3 requires specific operating facility data for all the components in Equation 4.24, whereas Tier 2 is based on default values for some of the components. Section 4.4.2.2 below provides details on parameters to be used:.

EQUATION 4.24[6]
CO_2 EMISSIONS FROM PASTE CONSUMPTION (TIER 2 AND TIER 3 METHODS)

$$E_{CO2} = \left(PC \bullet MP - \frac{CSM \bullet MP}{1000} - \frac{BC}{100} \bullet PC \bullet MP \bullet \frac{S_p + Ash_p + H_p}{100} \right.$$
$$\left. - \frac{100 - BC}{100} \bullet PC \bullet MP \bullet \frac{S_c + Ash_c}{100} - MP \bullet CD \right) \bullet \frac{44}{12}$$

Where:

E_{CO2} = CO_2 emissions from paste consumption, tonnes CO_2

MP = total metal production, tonnes Al

PC = paste consumption, tonnes/tonne Al

CSM = emissions of cyclohexane soluble matter, kg/tonne Al

BC = binder content in paste, wt %

S_p = sulphur content in pitch, wt %

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[6] An acceptable alternative method is to use the parameter of 'pitch coking' in lieu of deducting measured or default values for S_p, H_p, Ash_p and CSM from Equation 4.24. The pitch coking value is a commonly determined parameter for many facilities with Søderberg cells and standard methodology for performing the pitch coking test is described in ASTM D2416.

Ash_p = ash content in pitch, wt %

H_p = hydrogen content in pitch, wt %

S_c = sulphur content in calcined coke, wt %

Ash_c = ash content in calcined coke, wt %

CD = carbon in skimmed dust from Søderberg cells, tonnes C/tonne Al

44/12 = CO_2 molecular mass : carbon atomic mass ratio, dimensionless

Equation 4.24 should be applied to each smelter in the country using the Søderberg process and the results summed to arrive at total national emissions. It is possible to use a hybrid Tier 2/3 approach if data on ash or sulphur content are not available for each smelter.

4.4.2.2 CHOICE OF EMISSION FACTORS FOR CO_2 EMISSIONS FROM PRIMARY ALUMINIUM PRODUCTION

Tier 1 method for CO_2 emissions

Table 4.10 lists the default emission factors for CO_2 per tonne of aluminium. The emission factors of 1.6 and 1.7 for Prebake and Søderberg technologies are based on International Aluminium Institute (IAI) global survey data (International Aluminium Institute, Life Cycle Assessment of Aluminium, 2000).

TABLE 4.10
TIER 1 TECHNOLOGY SPECIFIC EMISSION FACTORS FOR CALCULATING CARBON DIOXIDE EMISSIONS FROM ANODE OR PASTE CONSUMPTION

Technology	Emission Factor (tonnes CO_2/tonne Al)	Uncertainty (+/-%)
Prebake[7]	1.6	10
Søderberg	1.7	10

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

Tier 2 and Tier 3 emission factors for CO_2 emissions

***CO_2 emissions for Prebake cells (CWPB and SWPB)*:**

The most significant factors in Equation 4.21 are metal production and net anode consumption for Prebake technology. Both these parameters should be collected from individual operating facilities for use with the Tier 2 or the Tier 3. Other terms in the equation make minor adjustments for non-carbon components of the anodes (for example, sulphur and ash) and thus are not as critical. Tier 3 is based on the use of specific operating facility data for these minor components, whereas Tier 2 is based on default values listed in Tables 4.11 to 4.13. Tier 3 improves the accuracy of the results, but the improvement in accuracy is not expected to exceed 5 percent. Carbon consumed per tonne of aluminium produced is typically recorded by primary aluminium production facilities given its economic significance. Facilities using prebake cells refer to this consumption as 'net anode or net carbon consumption,' and those using Søderberg cells refer to it as 'anode paste consumption.'

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[7] The emission factor for Prebake cells includes CO_2 emissions from the combustion of pitch volatiles and packing coke from baking anodes.

TABLE 4.11
DATA SOURCES AND UNCERTAINTIES FOR PARAMETERS USED IN TIER 2 OR 3 METHOD FOR CO_2 EMISSIONS FROM PREBAKE CELLS (CWPB AND SWPB), SEE EQUATION 4.21

Parameter	Tier 2 Method		Tier 3 Method	
	Data Source	**Uncertainty (+/-%)**	**Data Source**	**Uncertainty (+/-%)**
MP: total metal production (tonnes aluminium per year)	Individual facility records	2	Individual facility records	2
NAC: net anode consumption per tonne of aluminium (tonnes per tonne Al)	Individual facility records	5	Individual facility records	5
S_a: sulphur content in baked anodes (wt %)	Use industry typical value, 2	50	Individual facility records	10
Ash_a: ash content in baked anodes (wt %)	Use industry typical value, 0.4	85	Individual facility records	10
Source: IAI (2005b).				

TABLE 4.12
DATA SOURCES AND UNCERTAINTIES FOR PARAMETERS USED IN TIER 2 OR 3 METHOD FOR CO_2 EMISSIONS FROM PITCH VOLATILES COMBUSTION (CWPB AND SWPB), SEE EQUATION 4.22

Parameter	Tier 2 Method		Tier 3 Method	
	Data Source	**Uncertainty (+/-%)**	**Data Source**	**Uncertainty (+/-%)**
GA: initial weight of green anodes processed (tonnes green anode per year)	Individual facility records	2	Individual facility records	2
H_w: Hydrogen content in green anodes (tonnes)	Use industry typical value, 0.005 • GA	50	Individual facility records	10
BA: Baked anode production (tonnes per year)	Individual facility records	2	Individual facility records	2
WT: Waste tar collected (tonnes) a) Riedhammer furnaces b) All other furnaces	Use industry typical value, a) 0.005 • GA b) insignificant	50	Individual facility records	20
Source: IAI (2005b).				

TABLE 4.13
DATA SOURCES AND UNCERTAINTIES FOR PARAMETERS USED IN TIER 2 OR 3 METHOD FOR CO_2 EMISSIONS FROM BAKE FURNACE PACKING MATERIAL (CWPB AND SWPB), SEE EQUATION 4.23

Parameter	Tier 2 Method		Tier 3 Method	
	Data Source	**Uncertainty (+/-%)**	**Data Source**	**Uncertainty (+/-%)**
PCC: Packing coke consumption (tonnes per tonne BA)	Use industry typical value, 0.015	25	Individual facility records	2
BA: Baked anode production (tonnes per year)	Individual facility records	2	Individual facility records	2
S_{pc}: Sulphur content in packing coke (wt %)	Use industry typical value, 2	50	Individual facility records	10
Ash_{pc}: Ash content in packing coke (wt %)	Use industry typical value, 2.5	95	Individual facility records	10
Source: IAI (2005b).				

***CO_2 emissions for Søderberg cells (VSS and HSS)*:**

The binder content in paste, BC, typically varies by less than 1 percent and is part of operation practice by facility. It is an important term in Equation 4.24 because the carbon content of the pitch, which acts as a binder, is lower than that of the coke, which makes up the remainder of the paste. As was noted previously for Prebake anode consumption, the most important components of Equation 4.24 are the metal production and paste consumption. The other terms in Equation 4.24 make small corrections based on impurities and minor differences in carbon content of paste materials. Tier 3 is based on the use of specific operating facility data for these minor components, whereas Tier 2 is based on default values listed in Table 4.14. Tier 3 improves the accuracy of the results; however, the impact can be expected to be less than 5 percent on the result.

TABLE 4.14
DATA SOURCES AND UNCERTAINTIES FOR PARAMETERS USED IN TIER 2 OR 3 METHOD FOR CO_2 EMISSIONS FROM SØDERBERG CELLS (VSS AND HSS)

Parameter	Tier 2 Method		Tier 3 Method	
	Data Source	Data Uncertainty (+/-%)	Data Source	Data Uncertainty (+/-%)
MP: total metal production (tonnes Al/year)	Individual facility records	2	Individual facility records	2
PC : paste consumption (tonnes per tonne Al)	Individual facility records	2-5	Individual facility records	2-5
CSM: emissions of cyclohexane soluble matter (kg per tonne Al)	Use industry typical value, HSS – 4.0 VSS – 0.5	30	Individual facility records	15
BC: binder content in paste (wt %)	Use industry typical value, Dry Paste – 24 Wet Paste – 27	25	Individual facility records	5
S_p: sulphur content in pitch (wt %)	Use industry typical value, 0.6	20	Individual facility records	10
Ash_p: ash content in pitch (wt %)	Use industry typical value, 0.2	20	Individual facility records	10
H_p: hydrogen content in pitch (wt %)	Use industry typical value, 3.3	50	Individual facility records	10
S_c: sulphur content in calcined coke (wt %)	Use industry typical value, 1.9	20	Individual facility records	10
Ash_c: ash content in calcined coke (wt %)	Use industry typical value, 0.2	50	Individual facility records	10
CD: carbon in dust from anode (tonnes of carbon in skim per tonne Al)	Use industry typical value, 0.01	99	Individual facility records	30

4.4.2.3 CHOICE OF METHOD FOR PFCS

During electrolysis, alumina (Al_2O_3) is dissolved in a fluoride melt comprising about 80 weight percent cryolite (Na_3AlF_6). Perfluorocarbons (CF_4 and C_2F_6 collectively referred to as 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.

BOX 4.2

ANODE EFFECT DESCRIPTION

An anode effect is a process upset condition where an insufficient amount of alumina is dissolved in the electrolyte, causing voltage to be elevated above the normal operating range, resulting in the emission of PFC-containing gases.

Both Tier 2 and Tier 3 for 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 PFC inventory should be utilized with slope or overvoltage coefficients calculated from measurement data obtained using good measurement practices (U.S. EPA and IAI, 2003). 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 or anode effect overvoltage. PFC emissions are directly related to anode effect performance via a coefficient, either the slope coefficient or the overvoltage coefficient.

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 that emit very small amounts of PFCs, the Tier 3 method will likely not provide a significant improvement in the overall facility GHG inventory in comparison with the Tier 2 Method.[8] 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 0.2 anode effect minutes per cell day when anode effect minutes are measured. When overvoltage is recorded, high performing facilities operate with less than 1.4 mV overvoltage. In addition, for these high performing facilities accurate measurement of the Tier 3 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: Use of technology based default emission factors

The Tier 1 method uses technology-based default emission factors for the four main production technology types (CWPB, SWPB, VSS and HSS). PFC emissions can be calculated according to Equation 4.25. The level of uncertainty in the Tier 1 method is much greater because individual facility anode effect performance, which is the key determinant of anode effects and thus PFC emissions, 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.

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[8] The levels for the process parameters that define high performing facilities for PFC emissions are the combined result of the magnitude of, and, the uncertainty in the Tier 2 coefficient. The levels are calculated by using the positive and negative extremes of the 95% confidence limits for the Tier 2 coefficient as a proxy for the range of likely values for Tier 3 coefficients for these facilities. The potential difference is then assessed on the overall greenhouse gas emissions from a production facility considering both PFC and CO_2 emissions. When facilities operate at or below the anode effect process parameter levels noted here for high performing facilities, the impact of moving from the Tier 2 method for PFCs to the Tier 3 method would not result in a change greater than 5% in overall GWP weighted GHG emissions. PFC emissions from high performing facilities account for less than 3% of global PFC emissions based on IAI 2004 anode effect survey data.

EQUATION 4.25
PFC EMISSIONS (TIER 1 METHOD)

$$E_{CF4} = \sum_i \left(EF_{CF4,i} \bullet MP_i \right)$$

and

$$E_{C2F6} = \sum_i \left(EF_{C2F6,i} \bullet MP_i \right)$$

Where:

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

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

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

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

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

Tier 2 and Tier 3 methods: based on anode effect performance

There are two different equations for estimating individual plant CF_4 emissions, which are both based on the relationship between anode effect and performance. These are the slope and overvoltage coefficient equations. Both types of coefficients are based on direct measurements of PFCs. Tier 2 makes use of an average coefficient from measurements at numerous facilities while Tier 3 is based on measurements at the individual facility. Because the process mechanisms that produce PFC emissions 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 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. The choice between the two estimation relationships depends on the process control technology in use. Equation 4.26 should be used when anode effect minutes per cell day are recorded and Equation 4.27 should be used when overvoltage data are recorded.

Slope Coefficient: The slope coefficient represents the kg of CF_4 per tonne of aluminium produced, divided by anode effect minutes per cell-day[9]. Since PFC emissions are measured per tonne of aluminium produced, it includes the effects of cell amperage and current efficiency, the two main factors determining the amount of aluminium produced in the cell. Equation 4.26 describes the slope method for both CF_4 and C_2F_6.

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

$$E_{CF4} = S_{CF4} \bullet AEM \bullet MP$$

and

$$E_{C2F6} = E_{CF4} \bullet F_{C2F6/CF4}$$

Where:

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

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

S_{CF4} = 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

$F_{C2F6/CF4}$ = weight fraction of C_2F_6/CF_4, kg C_2F_6/kg CF_4

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[9] The term 'cell-day' refers to the number of cells operating multiplied by the number of days of operation.

Overvoltage Coefficient: Some process control systems characterize anode effects by calculating an Anode Effect Overvoltage[10] (AEO) statistic. AEO is defined as the extra cell voltage above the target operating voltage, and this parameter has been shown to be a good predictor of PFC emissions when recorded by the process control system. The AEO process control technology is in use at many modern smelters. AEO is calculated by summing the product of time and voltage above the target operating voltage and dividing this figure by the time over which data were collected.

EQUATION 4.27

PFC EMISSIONS BY OVERVOLTAGE METHOD (TIER 2 AND TIER 3 METHODS)

$$E_{CF4} = OVC \bullet \frac{AEO}{CE/100} \bullet MP$$

and

$$E_{C2F6} = E_{CF4} \bullet F_{C2F6/CF4}$$

Where:

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

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

OVC = Overvoltage coefficient for CF_4, (kg CF_4/tonne Al)/mV

AEO = anode effect overvoltage, mV

CE = aluminium production process current efficiency expressed, percent (e.g., 95 percent)

MP = metal production, tonnes Al

$F_{C2F6/CF4}$ = weight fraction of C_2F_6/CF_4, kg C_2F_6/kg CF_4

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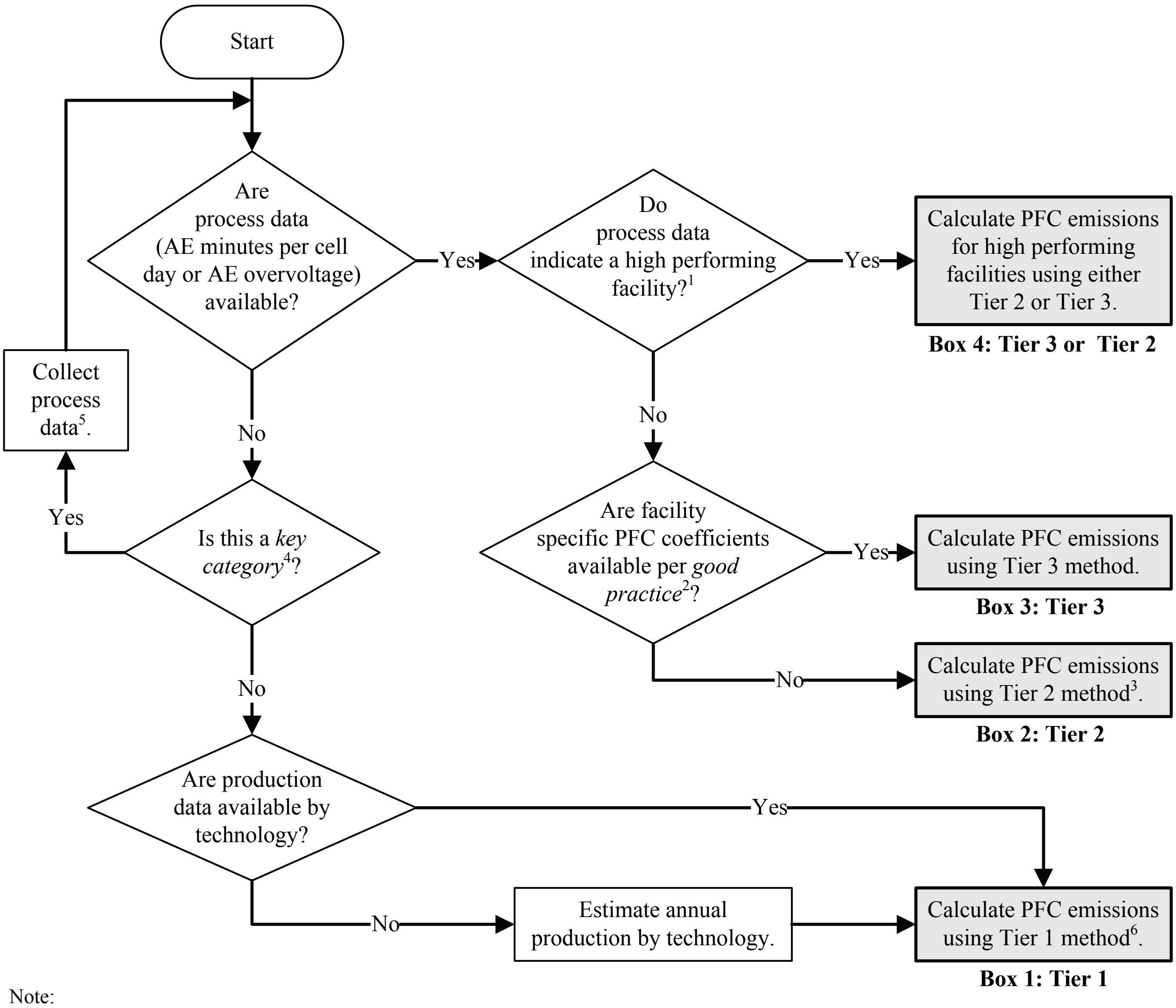
[10] Computer control systems report either ‘positive’ or ‘algebraic’ overvoltage depending on the version of software used. Use of the expression ‘overvoltage’ should not be confused with the classical electrochemical terminology, which usually means the extra voltage needed for an electrochemical reaction to occur.

Figure 4.12 Decision tree for calculation of PFC emissions from primary aluminium production



Note:

1. High performing facilities emit so little PFCs that no significant improvement can be expected in the overall facility GHG inventory by using the Tier 3 method rather than the Tier 2 method. High performing facilities are defined, based on what process data are collected, as those that operate with less than 0.2 anode effect minutes per cell day, or, less than 1.4 mV overvoltage. In such facilities the improvement in accuracy in facility GHG inventory is less than 5% when moving from Tier 2 to Tier 3 methods for PFCs.
2. *Good practices* for obtaining facility specific PFC equation coefficients are detailed in the IAI GHG Protocol (IAI, 2005).
3. In this case, Tier 2 method should be used until site-specific Tier 3 coefficients become available and the Tier 3 method employed unless PFC emissions become immaterial, in which case facilities can choose to use either the Tier 2 or Tier 3 method.
4. 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.
5. For *key categories*, it is *good practice* to collect anode effect process data and production activity data at the individual production facility level.
6. Primary aluminium facilities regularly record activity data including metal production and anode effect process data facilitating, at a minimum, Tier 2 calculation method. Errors of magnitude of x10 can result from use of Tier 1 methods for PFCs.

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
DEFAULT EMISSION FACTORS AND UNCERTAINTY RANGES FOR THE CALCULATION OF PFC EMISSIONS FROM ALUMINIUM PRODUCTION BY CELL TECHNOLOGY TYPE (TIER 1 METHOD)

Technology	CF_4		C_2F_6	
	EF_{CF4} (kg/tonne Al)[a]	Uncertainty Range (%)[b]	EF_{C2F6} (kg/tonne Al)[c]	Uncertainty Range (%)[d]
CWPB	0.4	-99/+380	0.04	-99/+380
SWPB	1.6	-40/+150	0.4	-40/+150
VSS	0.8	-70/+260	0.04	-70/+260
HSS	0.4	-80/+180	0.03	-80/+180

[a] Default CF_4 values calculated from median anode effect performance from 1990 IAI survey data (IAI, 2001).

[b] Uncertainty based on the range of calculated CF_4 specific emissions by technology from 1990 IAI anode effect survey data (IAI, 2001).

[c] Default C_2F_6 values calculated from global average C_2F_6:CF_4 ratios by technology, multiplied by the default CF_4 emission factor.

[d] Uncertainty range based on global average C_2F_6:CF_4 ratios by technology, multiplied by calculated minimum and maximum specific CF_4 emissions from 1990 IAI survey data (IAI, 2001).

Note: These default emission factors should only be used in the absence of Tier 2 or Tier 3 data.

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

The Tier 2 method is based on using either technology specific slope or overvoltage coefficients for the applicable reduction cell and process control technology as listed in Table 4.16.[11]

TABLE 4.16
TECHNOLOGY SPECIFIC SLOPE AND OVERVOLTAGE COEFFICIENTS FOR THE CALCULATION OF PFC EMISSIONS FROM ALUMINIUM PRODUCTION (TIER 2 METHOD)

Technology[a]	Slope Coefficient[b, c] [(kg $_{PFC}$/t_{Al}) / (AE-Mins/cell-day)]		Overvoltage Coefficient[b, c, d] [(kg $_{CF4}$/t_{Al}) / (mV)]		Weight Fraction C_2F_6 / CF_4	
	CF_4	Uncertainty (+/-%)	CF_4	Uncertainty (+/-%)	C_2F_6/CF_4	Uncertainty (+/-%)
CWPB	0.143	6	1.16	24	0.121	11
SWPB	0.272	15	3.65	43	0.252	23
VSS	0.092	17	NR	NR	0.053	15
HSS	0.099	44	NR	NR	0.085	48

[a] Centre Worked Prebake (CWPB), Side Worked Prebake (SWPB), Vertical Stud Søderberg (VSS), Horizontal Stud Søderberg (HSS).

[b] Source: Measurements reported to IAI, US EPA sponsored measurements and multiple site measurements (U.S. EPA and IAI, 2003).

[c] Embedded in each Slope and Overvoltage coefficient is an assumed emissions collection efficiency as follows: CWPB 98%, SWPB 90%, VSS 85%, HSS 90%. These collection efficiencies have been assumed based on measured PFC collection fractions, measured fluoride gas collection efficiencies and expert opinion.

[d] The noted coefficients reflect measurements made at some facilities recording positive overvoltage and others recording algebraic overvoltage. No robust relationship has yet been established between positive and algebraic overvoltage. Positive overvoltage should provide a better correlation with PFC emissions than algebraic overvoltage. Overvoltage coefficients are not relevant (NR) to VSS and HSS technologies.

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[11] These slope coefficients were derived from measurement of PFCs and correlating the measured PFC emissions to anode effect minutes per cell day at over one-hundred aluminium smelters. The values in Table 4.16 are the technology specific factors from measurement data available as of March 2005 when this document was developed. It is important to note Tier 2 slope coefficients are based on the anode-effect minutes per cell-day statistic as defined in the IAI GHG Protocol (IAI, 2005a). It is *good practice* to refer to the most current data for calculation of PFC emissions as noted in the IAI GHG Protocol and to the IPCC Emission Factor Database.

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 a facility specific slope or anode effect overvoltage PFC coefficient. This coefficient characterizes the relationship between facility anode effect performance and measured PFC emissions from periodic or continuous measurements that are consistent with established measurement practices (U.S. EPA and IAI*,* 2003) and the International Aluminium Institute GHG Protocol (IAI, 2005a).

4.4.2.5 CHOICE OF ACTIVITY DATA

Production statistics should be available from every facility to enable use of Tier 1 methods for both CO_2 and PFC emissions. Uncertainty in the 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 require accurate anode effect minutes per cell day data or accurate overvoltage (AEO) data for all cell types. Annual statistics should be based on the production-weighted average of monthly anode effect data. Both Tier 2 and Tier 3 utilize anode effect minutes per cell day or anode effect overvoltage, and aluminium production data. 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 CO_2 emissions, all aluminium smelters collect data to support Tier 2 or Tier 3 methods. Søderberg smelters collect anode paste consumption data while Prebake smelters record baked anode consumption. The Tier 2 and Tier 3 methods use the same equation for calculation of CO_2 emissions; however, the Tier 3 method uses facility specific composition data for anode materials while the Tier 2 method uses industry average anode composition data.

4.4.2.6 COMPLETENESS

Primary aluminium facilities will generally have good records of tonnes of aluminium produced throughout the entire time series covered by the inventory. In addition, carbon consumption data are typically available over the same period. Anode effect process data may be incomplete over the entire time series and measures may have to be employed, such as those described in Section 4.4.2.7, Developing a Consistent Time Series, to calculate PFC emissions over some portions of the inventory period. Primary aluminium production also utilizes large amount of electricity and care should be exercised to avoid omissions of carbon dioxide associated with electricity input, or, to avoid double counting of this carbon dioxide.

4.4.2.7 DEVELOPING A CONSISTENT TIME SERIES

Aluminium production statistics will typically be available for the entire history of the facility. Developing a consistent time series for carbon dioxide emissions should not be a problem since most facilities historically have measured and recorded anode or paste consumption. Where historic anode or paste consumption data are missing, carbon dioxide emissions can be estimated from aluminium production utilizing the Tier 1 method.

A complete time series of PFC related activity data such as anode effect 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 anode effect frequency data are available and anode effect duration data are unavailable, it is *good practice* to splice or backcast PFC emissions per tonne aluminium based on anode effect frequency data. 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, whether there have been substantial changes in work practices, whether any changes in the calculation of underlying process data have occurred, and the quality of the measurements made to establish the Tier 3 coefficients. 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 (IAI, 2005). Expert advice is also available from the International Aluminium Institute (London, UK) regarding greenhouse gas emissions and typical industry emissions from aluminium production.

4.4.3 Uncertainty assessment

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 Søderberg cells. These factors are both carefully monitored and are important factors in the economic performance of a facility. Improvements in accuracy of carbon dioxide emissions inventories can be achieved by moving from Tier 1 to Tier 2 methods because there is a range of performance of reduction facilities in the consumption of carbon anode materials. Less significant improvements in accuracy can be expected in choosing the Tier 3 method over the Tier 2 method. This is because the major factors in the calculation are the net anode carbon consumed or paste consumption and the production of aluminium. The uncertainty of both these components of the calculation equation is low, 2 to 5 percent, and these uncertainties dominate the overall calculation of carbon dioxide emissions in the Tier 2 and Tier 3 methods. Facility specific data are used in both Tier 2 and Tier 3 calculations for these parameters. The Tier 3 method refines the calculation to use actual composition of the carbon anode materials. While there can be considerable variability in the minor components of the anode materials this variability does not contribute significantly to the overall calculation of carbon dioxide emissions.

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. 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; however, the level of uncertainty reduction depends on the cell technology type. The uncertainty for industry average coefficients ranges from +/-6 percent for CWPB, the most widely measured and used technology, to +/-44 percent for HSS. 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. As more facility measurements are made, especially in those facilities operating with Søderberg technologies, the uncertainty in the average coefficients should be reduced. The lowest uncertainty for PFC emissions calculations 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 (USEPA/IAI, 2003). When properly established these Tier 3 coefficients will have an uncertainty of +/-15 percent at the time the coefficients are measured.

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., either anode effect minutes per cell day or anode effect overvoltage. 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

4.4.4.1 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

It is *good practice* at all primary aluminium production facilities to maintain records of all of the necessary activity data to support calculations of emissions factors as suggested in these guidelines. These records will include production of aluminium, anode effect performance and consumption of carbon materials used in either Prebake or Søderberg cells. In addition, the International Aluminium Institute maintains global summaries of aggregated activity data for these same parameters and regional data are available from regional aluminium associations. It is *good practice* to aggregate emissions estimates from each smelter to estimate total national emissions. However, if smelter-level production data are unavailable, smelter capacity data may be used along with aggregate national production to estimate smelter production.

It is *good practice* to verify facility CO_2 emission factors per tonne aluminium by comparison with the expected range of variation that would be predicted from the variation noted in Tables 4.10 and 4.11 for carbon dioxide specific emissions. Also, the underlying equation coefficients used for calculating PFC emission factors per tonne aluminium should be compared with those noted 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 (CF_4) and Hexafluoroethane (C_2F_6) Emissions from Primary Aluminum Production is the internationally recognized standard (U.S. EPA and IAI, 2003). Inventory compilers should encourage plants to use this method for developing Tier 3 PFC equation coefficients. 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 PFCs per tonne of aluminium may change by values of up to +/- 100 percent. Increases in PFC specific emissions can result from process instability. Increases in anode effect frequency and duration can be the result of factors such as unanticipated power interruptions, changes in sources of alumina feed materials, cell operational problems, and increases in potline amperage to increase aluminium production. Decreases in PFC specific emissions can result from decreases in anode effect frequency and duration due to changes in the computer algorithms used in cell process control, upgrades in cell technology such as the installation of point feeders, improved work practices and better control of raw materials.

4.4.4.2 REPORTING AND DOCUMENTATION

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Volume 1, Chapter 6, Quality Assurance and Quality Control, Internal Documentation and Archiving. Some examples of specific documentation and reporting relevant to this source category are provided below.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced. To improve transparency, it is *good practice* to report emissions for PFCs from aluminium production separately from other source categories. Additionally, it is *good practice* that CF_4 and C_2F_6 emissions are reported separately on a *mass basis*.

The supporting information necessary to ensure transparency in reported emissions estimates is shown in Table 4.17, *Good practice* Reporting Information for PFC Emissions from Aluminium Production by Tier, below.

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

TABLE 4.17

GOOD PRACTICE REPORTING INFORMATION FOR CALCULATING CO_2 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
CO_2			
Annual national production (by Prebake or Søderberg technology)			X
Annual production by smelter (by Prebake or Søderberg technology)	X	X	
Net anode consumption for Prebake cells or paste consumption for Søderberg cells	X	X	
Carbon material impurity levels and carbon dust for Søderberg cells	X		

4.5 MAGNESIUM PRODUCTION

4.5.1 Introduction

In the magnesium industry, there are a number of potential emission sources and gases. The amount and type of emission from the magnesium industry will reflect the raw material used for primary magnesium metal production and/or the type of cover gas mixture used in the casting and recycling foundries to prevent oxidation of molten magnesium. It is *good practice* to consider, in a disaggregated way if possible, all segments of the magnesium industry and their related emissions. A list of possible greenhouse gas emissions, which may be associated with primary, and secondary magnesium metal production and casting operations, is provided in Table 4.18.

Primary magnesium refers to metallic magnesium derived from mineral sources. Primary magnesium can be produced either by electrolysis or a thermal reduction process. The raw materials used for primary magnesium production are dolomite, magnesite, carnalite, serpentine, brines or seawater. Processing of carbonate raw materials (magnesite and dolomite) will release CO_2 during manufacturing. The CO_2 is released during calcination of carbonate-based ores (dolomite/magnesite) - a ‘pre-treatment’ step to the main electrolytic/thermal reduction processes. This process is similar to the generation of CO_2 in the mineral industry (see Chapter 2).

Secondary magnesium production includes the recovery and recycling of metallic magnesium from a variety of magnesium containing scrap materials e.g., post consumer parts, machine cuttings, casting scraps, furnace residues, etc. Magnesium casting processes may involve metal from both primary production and secondary magnesium production. Magnesium casting processes involve handling of molten pure magnesium and/or molten high magnesium content alloys. Molten magnesium (also understood to mean high magnesium content alloys) maybe cast by a variety of methods including gravity casting, sand casting, die casting and others.

All molten magnesium spontaneously burns in the presence of atmospheric oxygen. Production and casting of all magnesium metal requires a protection system to prevent burning. Among the various protection systems commonly used are those that use gaseous components with high GWP values, such as SF_6, which typically escape to the atmosphere. Metallic magnesium cast from the various processes and sources all require protection methods and will therefore have similar potentials for GHG emissions.

TABLE 4. 18
POSSIBLE GHG EMISSIONS RELATED TO PRODUCTION AND PROCESSING OF MAGNESIUM

PROCESS	POTENTIAL ASSOCIATED PROCESS GHG EMISSION			
	SF$_6$	***HFC’s***	***CO$_2$***	***Others****
Raw Materials Preparation for Primary Production				
Dolomite/Magnesite Based	-	-	X	-
Other Raw Materials	-	-	-	-
Casting (primary & secondary)				
Primary ingot casting	X	X	X	X
Die casting	X	X	X	X
Gravity casting	X	X	X	X
Other casting methods	X	X	X	X
Secondary Mg Production**	X	X	X	X

*Others include fluorinated ketone and various fluorinated decomposition products e.g., PFCs

** Includes processes involving the recycle/recovery of metallic magnesium

Secondary magnesium production (recycling), handling, melting, and casting, molten metal is protected against oxidation throughout the process by using protection systems such as SF_6 or SO_2 containing cover gases (a carrier gas (commonly air and/or CO_2) and SF_6 or SO_2[12]) or, in some cases, flux. High-magnesium content alloys are also commonly protected using SF_6 containing cover gases. Due to recent technological developments and a push towards the replacement of SF_6, the magnesium industry has introduced alternative cover gases. It is foreseen that the two most common alternatives to SF_6 in the next decade will be the fluorinated hydrocarbon HFC-134a and the fluorinated ketone FK 5-1-12 ($C_3F_7C(O)C_2F_5$), traded under the name Novec™612[13], and that the individual magnesium producer's/processor's choice of cover gas will be strongly influenced by national/regional circumstances (Tranell *et al*., 2004).

CO_2 EMISSIONS FROM PRIMARY PRODUCTION

As indicated in Table 4.18, the magnesium-containing ores which release CO_2 during calcination are dolomite ($Mg{\bullet}Ca(CO_3)_2$) and magnesite ($MgCO_3$). For each kilogram of magnesium produced, theoretically 3.62 kg[14] (dolomite) or 1.81 kg (magnesite) respectively of CO_2, is emitted during calcination. The actual CO_2 emissions per kilogram magnesium produced will be higher than the theoretical emission due to losses of magnesium in the process chain.

MAGNESIUM CASTING PROCESSES (PRIMARY & SECONDARY)

In magnesium casting processes, the size and type of GHG emission will depend on the chosen cover gas system used to protect liquid magnesium. In addition to emissions of the active protection compound (SF_6, HFC-134a or FK 5-1-12) in the cover gas itself – there may be emissions of various fluorinated decomposition products (e.g., PFCs) and potentially also the carrier gas (depending on choice of air and/or CO_2 or N_2).

SF_6

It has been a common assumption that SF_6 in magnesium cover gas is inert and that hence, essentially all SF_6 used in the magnesium industry will be emitted. However, recent independent studies (Bartos *et al*., 2003 and Tranell *et al*., 2004) demonstrate that SF_6 does, to a certain degree, destruct in contact with liquid/gaseous magnesium at common magnesium holding/processing temperatures. The fraction of SF_6 destroyed in the furnace, as well as the type/amount of secondary gas products generated from the reaction with magnesium, will depend on pertaining operating conditions such as SF_6 concentration in cover gas, total cover gas flow-rate, size of reactive magnesium surface area, type of carrier gas used, furnace charging practises, etc.

HFC-134a, FK 5-1-12 and decomposition products (e.g., PFCs)

Both HFC-134a and FK 5-1-12 are less thermodynamically stable (and thus have much lower GWP) than SF_6. It is hence expected that these gases will decompose/react extensively in the contact with liquid/gaseous magnesium, leading to the production of various fluorinated gases (e.g., PFCs). Tranell et al., 2004 found that as a general rule of thumb, when SF_6 is replaced by HFC-134a, less than half the amount of active fluorinated compound on a molar basis is needed to protect a given magnesium surface (under otherwise identical conditions). When SF_6 replaces FK 5-1-12, less than a quarter of the quantity of active compound is needed. It was reported that, as is the case for SF_6, the amount of active compound in the in-going cover gas destroyed in the furnace depends on conditions such as compound concentration in in-going cover gas, total cover gas flow-rate, size of reactive magnesium surface area, type of carrier gas used, charging practises etc. It should be noted that emissions of PFCs as decomposition products would be more significant in terms of CO_2 equivalent than FK 5-1-12 emissions, given their relative radiative effects[15].

Carrier gases

Many cover gas systems use CO_2 as a carrier gas -alone or in combination with dry air- to dilute the active fluorinated compound and reduce the oxygen partial pressure in the furnace. It is a quantitatively reasonable assumption that all CO_2 used in the cover gas is emitted as CO_2. The amount of carbon dioxide cover gas used is much lower than the usual active agents in the cover gas system and can generally be disregarded.

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[12] Consistent with the scope of these Guidelines outlined in Volume 1, this chapter does not provide methods for estimating emissions of SO_2.

[13] FK 5-1-12 ($C_3F_7C(O)C_2F_5$), traded as Novec™612, is a fluorinated ketone produced by 3M (Milbrath, 2002).

[14] This represents a case where the ore has a stoichiometric Mg/Ca ratio of 1.

[15] The GWP value of FK 5-1-12 is not identified in the IPCC Third Assessment Report (IPCC, 2001), but it is estimated to be similar to that of CO_2 according to the producer of this gas.

4.5.2 Methodological issues

4.5.2.1 CHOICE OF METHOD

CO_2 EMISSIONS FROM PRIMARY PRODUCTION

The choice of a *good practice* method for inventory preparation of carbon dioxide emissions from the primary magnesium (raw material) production segment will depend on national circumstances. The decision tree (see Figure 4.13, Decision Tree for Estimation of CO_2 Emissions from Primary Magnesium Production) describes *good practice* in adapting the methods to these country-specific circumstances.

Tier 1

The Tier 1 method relies on national primary production data and knowledge of raw materials used in the country. National production data may not be publicly available as there are a limited number of countries producing magnesium and only a few individual producers - often only one in a country - often resulting in the designation of national production data as confidential. In the absence of national primary magnesium production statistics, industry associations, such as the International Magnesium Association (http://www.intlmag.org/), may be able to provide regional statistics. Failing other data, it may be possible to estimate primary magnesium production from annual national magnesium metal sales. This method has increased uncertainty, since it does not account for magnesium used in national product manufacturing.

CO_2 emissions are calculated using Equation 4.28.

EQUATION 4.28
CO_2 EMISSIONS FROM PRIMARY MAGNESIUM PRODUCTION (TIER 1)

$$E_{CO2} = \left(P_d \bullet EF_d + P_{mg} \bullet EF_{mg}\right) \bullet 10^{-3}$$

Where:

E_{CO2} = CO_2 emissions from primary magnesium production, Gg

P_d = national primary magnesium production from dolomite, tonnes

P_{mg} = national primary magnesium production from magnesite, tonnes

EF_d = Default emission factor for CO_2 emissions from primary magnesium production from dolomite, tonne CO_2/tonne primary Mg produced

EF_{mg} = Default emission factor for CO_2 emissions from primary magnesium production from magnesite, tonne CO_2/tonne primary Mg produced

Tier 2

The Tier 2 method for determining CO_2 emissions from primary magnesium involves collecting company/plant-specific empirical emission factors, in addition to company specific production data. The company specific emission factors may differ substantially from the default emission factors depending on process materials handling. This collection should take place if the emissions are a *key category*.

CO_2 emissions are calculated using Equation 4.29.

EQUATION 4.29
CO_2 EMISSIONS FROM PRIMARY MAGNESIUM PRODUCTION (TIER 2)

$$E_{CO2} = \sum_i (P_i \bullet EF_i) \bullet 10^{-3}$$

Where:

E_{CO2} = CO_2 emissions from primary magnesium production, Gg

P_i = primary magnesium produced in plant *i*, tonne

EF_i = company/plant-specific emission factor for CO_2 emissions from primary magnesium production obtained from company/plant *i*, tonne CO_2 /tonne primary Mg produced

Tier 3

If actual measured CO_2 emissions data are available from individual primary magnesium facilities, these data can be aggregated and used directly to account for national emissions.

MAGNESIUM CASTING PROCESSES (PRIMARY & SECONDARY)

SF_6

The choice of a *good practice* method for inventory preparation of SF_6 emissions from magnesium casting process segment will also depend on national circumstances. The decision tree (Figure 4.14, Decision Tree for Estimation of SF_6 Emissions from Magnesium Processing) describes *good practice* in adapting the methods to these country-specific circumstances.

Tier 1 – default emission factors

The Tier 1 method is based on the total amount of magnesium casting or handling in the country (Equation 4.30). The underlying assumption for the Tier 1 approach is that all SF_6 consumption in the magnesium industry segment is emitted as SF_6. As described in Section 4.5.1, this assumption will potentially overestimate the GHG emissions, but the overestimate will lie within the overall uncertainty range given in Section 4.5.3. The basic Tier 1 method uses a single value as a basis for the default emission calculation when SF_6 is used for oxidation protection, despite the fact that SF_6 consumption vary substantially between different casting operations and operators (sometimes orders of magnitude). The Tier 1 method should be used only when the inventory compiler has no knowledge of type of magnesium handling- or casting operation (recycling, billet casting or die-casting etc.)

EQUATION 4.30
SF_6 EMISSIONS FROM MAGNESIUM CASTING (TIER 1)

$$E_{SF6} = MGc \bullet EF_{SF6} \bullet 10^{-3}$$

Where

E_{SF6} = SF_6 emissions from magnesium casting, tonnes

MGc = total amount of magnesium casting or handling in the country, tonnes

EF_{SF6} = default emission factor for SF_6 emissions from magnesium casting, kg SF_6/tonne Mg casting

Tier 2 – company-specific SF_6 consumption

As for the Tier 1 method, the Tier 2 method also assumes that all SF_6 consumed is subsequentlyemitted. Instead of the amount of magnesium casting, however, the Tier 2 method uses data on national (or sub-national) consumption of SF_6 in the magnesium industry as reported by the industry or available through other sources such as national statistics (Equation 4.31).

The most accurate application of the method is normally collection of direct data on SF_6 consumption from all individual users of the gas in the magnesium industry. If no direct data are available, an alternative but a less accurate method is to estimate the share of annual national SF_6 consumption attributable to the magnesium industry. This requires collecting annual data on national SF_6 sales and assumes that all SF_6 gas sold to the magnesium industry is emitted within the year.

EQUATION 4.31
SF_6 EMISSIONS FROM MAGNESIUM CASTING (TIER 2)

$$E_{SF6} = C_{SF6}$$

Where

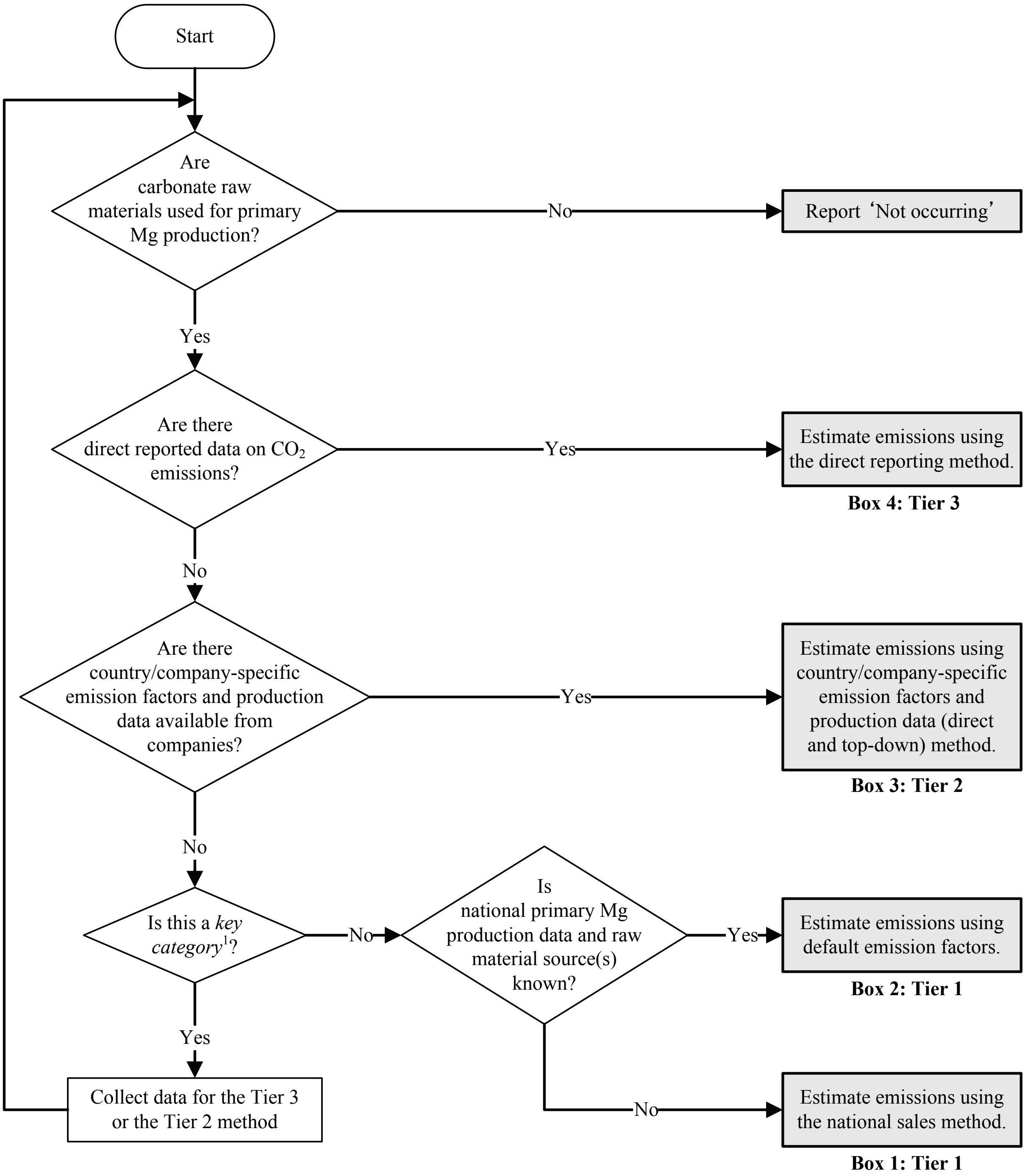
E_{SF6} = SF_6 emissions from magnesium casting, tonnes

C_{SF6} = consumption of SF_6 in magnesium smelters and foundries, tonnes

Tier 3 – direct measurement approach

If actual measured emission data are available from individual magnesium processing facilities, these data can be aggregated and used directly to account for national emissions. In such reporting, it is *good practice* to include destruction of SF_6 and formation of secondary gas products.

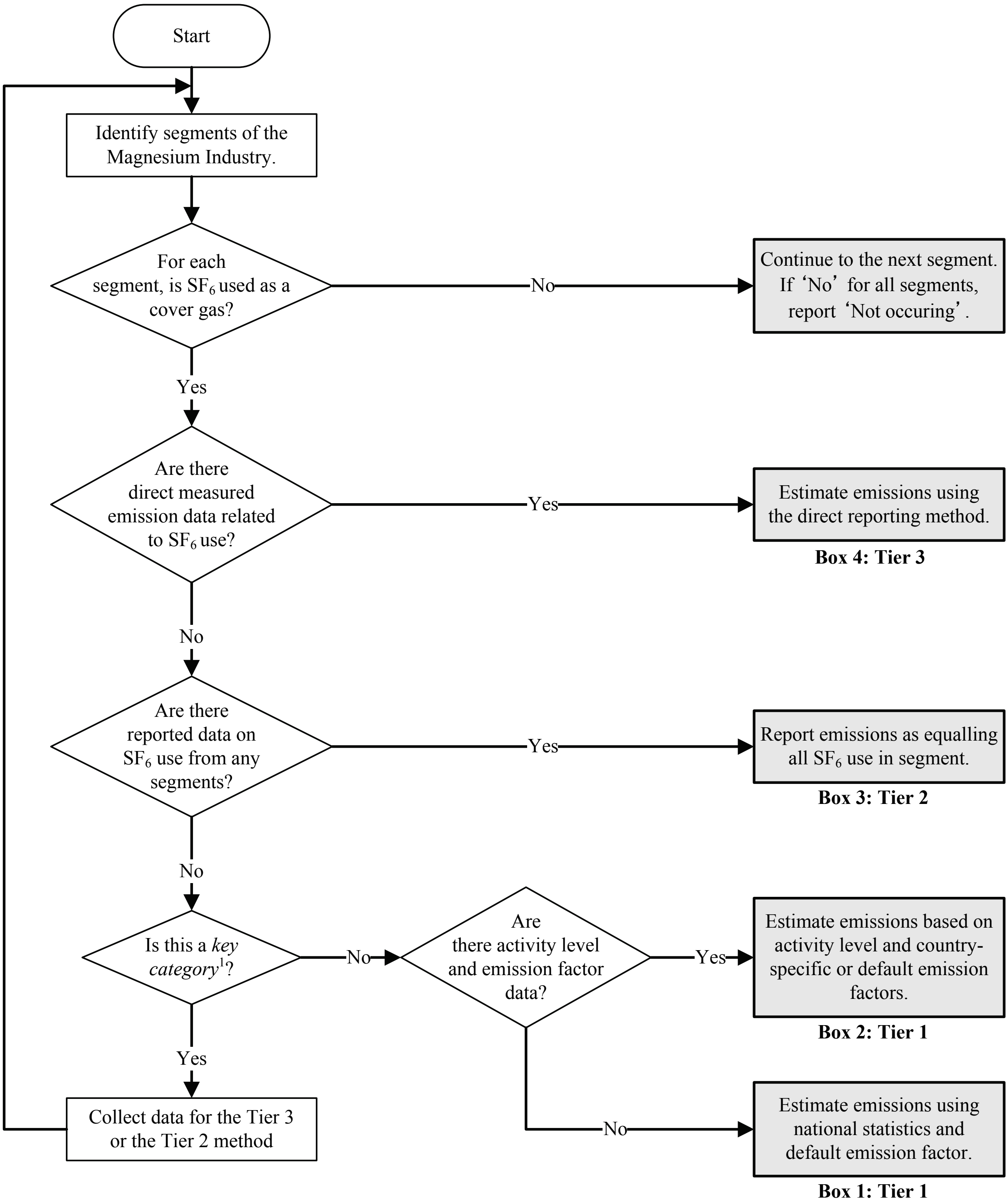
Figure 4.13 **Decision tree for estimation of CO_2 emissions from raw materials calcination in the primary magnesium production process**



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 4.14 Decision tree for estimation of SF_6 emissions from magnesium processing



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.

HFC-134a, FK 5-1-12 and decomposition products (e.g., PFCs)

As described in Section 4.5.1, the industrial use of fluorinated compounds other than SF_6 for magnesium oxidation protection commenced in 2003-2004. As such, the industrial experience in using these compounds for magnesium protection purposes is yet very limited. Even individual plants will have little historic data, if any, on actual emissions of these other fluorinated compounds from their operations. While there is a general sense in industry that the volume use of these alternate gases will be less than SF_6, there are no data available at this time on which to base emission factors. Hence, it is not possible at this time to develop an emission factor-based approach (Tier 1 or 2) for reporting emissions.

However, if the GHG emission from the use of magnesium cover gases is a national *key category*, it is *good practice* to collect direct measurements or meaningful indirect measurements of GHG emissions (fugitive emissions of HFC134-a and FK 5-1-12 as well as emissions of PFCs as decomposition products) from magnesium foundries using HFC-134a or FK 5-1-12 as cover gases. This is consistent with the Tier 3 approach.

Carrier gases

The contribution of carbon dioxide carrier gas used in protective cover gas systems is normally a small fraction of the global warming potential. In general, these emissions may be disregarded.

4.5.2.2 CHOICE OF EMISSION FACTORS

CO_2 EMISSIONS FROM PRIMARY PRODUCTION

Tier 1 – default emission factors

As previously mentioned, the Tier 1 method calculates emissions from default emission factors applied to a country's total primary magnesium production. The default emission factors (Table 4.19) take into account the type of material used and basic stoichiometric ratios which have been adjusted by empirical data for generic manufacturing process losses. The resulting emission of CO_2 per tonne magnesium produced is considerably higher than the theoretical volume described in the Section 4.5.1.

TABLE 4.19
EMISSION FACTORS FOR ORE-SPECIFIC PRIMARY Mg METAL PRODUCTION

Raw Material	tonnes CO_2 emission/tonne primary Mg produced
Dolomite	5.13
Magnesite	2.83

Tier 2 – country/company-specific emission factors

The Tier 2 method for estimating CO_2 emissions from primary magnesium involves collecting company/plant-specific empirical emission factors. The company specific emission factors may differ substantially from the default emission factors depending on process materials handling. This collection should take place if the emissions are a *key category*.

Tier 3 – direct measurement approach

If actual measured CO_2 emissions data are available from individual primary magnesium facilities, these data can be aggregated and used directly to account for national emissions.

MAGNESIUM CASTING PROCESSES (PRIMARY & SECONDARY)

SF_6

Tier 1 – default emission factors

The underlying assumption for the Tier 1 approach is that all SF_6 consumption in this industry segment is emitted, though. as described in Section 4.5.1, this assumption will potentially overestimate the GHG emissions. The Tier 1 method also assumes no knowledge of type of magnesium handling- or casting operation (recycling, billet casting or die-casting, etc.) Under recommended conditions for die-casting, the consumption rates are about 1 kg SF_6 per tonne magnesium produced or smelted (Gjestland and Magers, 1996). Although the SF_6

consumption vary substantially between different casting operations and operators (sometimes orders of magnitude), the basic Tier 1 method uses this value as a basis for the default emission calculation when SF_6 is used for oxidation protection. If the national magnesium manufacturing processes are well documented, a more accurate application of the Tier 1 method is to disaggregate production data and emission factors according to the various manufacturing processes. These emission factors should relate SF_6 emissions to magnesium production at the same disaggregated level as the available activity data (e.g., national, sub-national). National emission factors based on plant measurements are preferable to international default factors because they reflect conditions specific to the country. Such information may be accessible through industry associations, surveys or studies.

TABLE 4.20
SF_6 EMISSION FACTORS FOR MAGNESIUM CASTING PROCESSES (TIER 1)

Casting system	kg SF_6 emission per tonne Mg casting
All Casting Processes	1.0

Source: Gjestland and Magers (1996)

Tier 2 – company-specific SF_6 consumption

As for the Tier 1 method, the underlying principle for the Tier 2 method is that all SF_6 consumed is emitted. In the Tier 2 method it is, however, assumed the national (or sub-national) consumption of SF_6 in the magnesium industry is reported by the industry or available through other sources such as national statistics.

The most accurate application of the method is normally collection of direct data on SF_6 consumption from all individual users of the gas in the magnesium industry. If no direct data are available, an alternative but a less accurate method is to estimate the share of annual national SF_6 consumption attributable to the magnesium industry. This requires collecting annual data on national SF_6 sales and assumes that all SF_6 gas sold to the magnesium industry is emitted within the year.

Tier 3 – direct measurement approach

If actual measured emission data are available from individual magnesium processing facilities, these data can be aggregated and used directly to account for national emissions. In such reporting, it is *good practice* to include destruction of SF_6 and formation of secondary gas products.

HFC-134a, FK 5-1-12 and decomposition products (e.g., PFCs)

As described above, there are little historic data upon which to base emission factors. However, if the GHG emission from the use of magnesium cover gases is a national *key category*, it is *good practice*, for inventory preparation purposes, to collect direct measurements and or reliable indirect measures of GHG emissions (fugitive emissions of HFC134-a and FK 5-1-12 as well as emissions of PFCs as decomposition products) from magnesium foundries using HFC-134a or FK 5-1-12 as cover gases. This may be considered a Tier 3 approach. Over time, it may be possible to use Tier 3 measurements as a means of developing emission factors that could be used for Tier 2.

Carrier gases

As mentioned previously in this chapter, the contribution of carbon dioxide carrier gas used in protective cover gas systems is normally a small fraction of the global warming potential. In general it may be disregarded.

4.5.2.3 CHOICE OF ACTIVITY DATA

CO_2 EMISSIONS FROM PRIMARY PRODUCTION

For the Tier 1 method, inventory compilers need to obtain national primary production data and knowledge of raw material type used in the country. As discussed in Section 4.5.2.1, these data may not be publicly available and therefore be difficult to obtain, in particular for small-scale (particularly thermal reduction type) production units in developing countries. Approximate national magnesium production data may be available through industry associations such as the International Magnesium Association. For the Tier 2 method, inventory compilers need to collect primary magnesium production data and data on carbonate raw materials from each company/plant. With the Tier 3 method, activity data consists of direct measured and reported emissions.

MAGNESIUM CASTING PROCESSES (PRIMARY & SECONDARY)

SF_6

For the Tier 1 method, it is *good practice* to disaggregate production data into segments using SF_6, if possible, (e.g., primary production, recycling, billet casting, die casting, gravity casting, etc.) and apply available segment-specific emission factors. Where disaggregated data are not available, more aggregated production data, possibly combining output from several different processes, may be used to provide an estimate. In the absence of SF_6 consumption data or magnesium production data, the alternative is to collect annual national data on SF_6 sales to the magnesium industry. SF_6 producers may be able to provide these data directly, or they may be available from national statistics. It is *good practice* to consider data on consumption by other industries that use SF_6 (e.g., electrical equipment) when estimating the share consumed by the magnesium industry.

With the Tier 3 and 2 methods, the activity data are reported SF_6 (and secondary gas product) emissions or SF_6 consumption totals from each plant. For the Tier 1 method, national- or individual plant- magnesium production data are necessary. Where there is some direct reporting of SF_6 use in a segment, it is *good practice* to assess the share of production represented by the plants that directly report. For the other plants, it is *good practice* to use production-based estimates of emissions.

HFC-134a, FK 5-1-12 and decomposition products (e.g., PFCs)

With the Tier 3 method, activity data consists of direct measured and reported emissions. No Tier 1 or 2 method guidance is provided and hence, no activity data are necessary.

Carrier gases

It is *good practice* in inventory reporting that the chosen activity data for carrier gases are analogous to those of the active compound used. I.e., if CO_2 is used as carrier gas for SF_6, the activity data of CO_2 should reflect that of SF_6. If CO_2 is used as carrier for HFC-134a or FK 5-1-12, CO_2 activity data should reflect HFC-134a or FK 5-1-12 activity data.

4.5.2.4 COMPLETENESS

Incomplete direct reporting or incomplete activity data should not be a significant issue for primary production in developed countries. Typically, there are a small number of well-known primary magnesium producers in developed countries, and these producers are likely to keep good records. In developing countries, completeness issues generally arise in the casting segments, where facilities are more widely distributed, and have a wide range of capacities and technologies. Some plants may supply to niche markets not captured by national data sets. The inventory compiler should confirm the absence of estimates for these smaller industry segments rather than simply assuming they do not occur. It is also *good practice* to undertake periodic surveys of the industry and establish close links with international and local industry associations to check completeness of estimates.

Because alternate (non-SF_6) cover gas systems decompose to various fluorinated by-products, there may be some unaccounted global warming potential not described. This is not expected to be significant.

Since an increasing fraction of the world's primary production, as well as processing of magnesium, takes place in many small production units in countries with developing economies, completeness is expected to become a significant issue.

Inventory compilers should be cautious of the potential for double counting emissions from calcination of magnesium carbonate raw materials during primary magnesium production and those emissions associated with calcining limestone, dolomite, and other carboneous minerals (see Chapter 2, Other Process Uses of Carbonates, in this volume.) All emissions associated with the calcination of carbonates for primary magnesium production should be reported as GHG emissions from magnesium production.

4.5.2.5 DEVELOPING A CONSISTENT TIME SERIES

In terms of overall magnesium production statistics, these data will typically be available for the history of a plant. However, in some cases, historical production data may not be available due to lack of initial records or changes in the structure of the industry in the intervening period. In this case, production data from international sources may be used.

There may be issues with establishing a consistent time series for CO_2 emissions from primary magnesium production since these emissions may not have been reported prior to year 2006 (guidelines for reporting did not exist in the *Revised 1996 IPCC Guidelines* (IPCC, 1997)). For most primary magnesium production facilities it may, however, be assumed that the CO_2 emission level is relatively constant over time on a per tonne magnesium produced basis.

In terms of SF_6 emissions, it is *good practice* for the Tier 1 approach to multiply historic activity data by sub-national/national or default emission factor presently in use to establish consistent time series. It should be noted that plant specific emission factors would typically decrease over time due to environmental awareness, economic factors, and improved technologies and practices.

Since the magnesium industry did not use HFC-134a and FK 5-1-12 cover gases to a significant extent in any country prior to 2003, historic emissions will likely be zero. Given the level of complexity in reporting emissions related to the use of these gases, developing consistent time series will be a challenge to inventory compilers.

It is *good practice* to assess the appropriate historical emission factors following the guidance in Volume 1, Chapter 5. To ensure consistency over time, it is *good practice* to recalculate emissions estimates using previously used and new methods to ensure that any trends in emissions are real and not caused by changes in the estimation methodologies. *Good practice* is to document assumptions in all cases and archive them at the inventory compiler.

4.5.3 Uncertainty assessment

CO_2 EMISSIONS FROM PRIMARY PRODUCTION

At the plant level, there should normally be well-documented raw material type/analysis and use, as well as tonnage magnesium produced. Directly-reported activity data, which are required for Tier 2 and 3 methods for all gases, are typically accurate to within less than 5 percent. At the national inventory level, the accuracy of magnesium production activity and emission data is comparable to that of other national production statistics (i.e., ±5 percent). Additional uncertainty is introduced through estimating the share of production not reporting directly.

MAGNESIUM CASTING PROCESSES (PRIMARY & SECONDARY)

SF_6

In the Tier 1 approach, aggregating production from different secondary segments and using the default emission factor introduces uncertainty. For example, national data from casting operations may not be segregated into die-casting and gravity casting segments despite their potentially different SF_6 emission rates. Thus, this approach gives by default a very rough approximation of real emissions. Given that different handling and casting operations may use concentrations of SF_6 in cover gas that differ by orders of magnitude, uncertainties using the Tier 1 method may also range over orders of magnitude. For the Tier 1 and 2 methods, there is also a level of uncertainty associated with the assumption that 100 percent of the SF_6 used is emitted. In a typical casting operation, the uncertainty in this assumption should be within 30 percent (Bartos *et al*., 2003).

For the Tier 2 method, there is a very low uncertainty associated with SF_6 use on a plant level, since SF_6 use is measured easily and accurately from purchase data. (An uncertainty estimate of less than 5 percent is usually appropriate for directly reported data.)

For the Tier 3 method, uncertainties arise mainly from monitoring equipment calibration/accuracy. Typical gas analysis methods such as Fourier Transformed Infra Red Spectroscopy (FTIR) generally operate with an estimated accuracy of ± 10 percent. In addition to FTIR and similar analytical techniques, there will be further uncertainty caused by problems related to representative sampling and calibration that could raise the overall uncertainty of FTIR to ± 20 percent.

HFC-134a, FK 5-1-12 and decomposition products (e.g., PFCs)

As with the Tier 3 method for SF_6, main uncertainties are associated with monitoring equipment calibration/accuracy in processes using HFC-134a or FK 5-1-12 cover gases. Uncertainties are approximated to ± 10 percent.

Carrier gases

The largest uncertainty is associated with the Tier 1 approach of considering CO_2 emissions from cover gases negligible. This is particularly true if a facility uses a very CO_2 rich carrier gas blend. Other tiers have the same uncertainties as related for SF_6.

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

4.5.4.1 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Volume 1, Chapter 6, and an expert review of the emissions estimates. Additional quality control checks, as outlined in Volume 1, Chapter 6, and quality assurance procedures may also be applicable, particularly for higher tier methods. Inventory compilers are encouraged to use higher tier QA/QC for *key categories* as identified in Volume 1, Chapter 4.

The following section outlines additional procedures specific to magnesium production:

Comparison of emissions estimates using different approaches

If emissions were calculated using data from individual plants, inventory compilers should compare the estimate to emissions calculated using national magnesium production data or (in the case of SF_6) national consumption data attributed to magnesium use. The results of the comparison should be recorded and any discrepancies should be investigated.

Review of plant-level data

The following plant-specific information should be archived to facilitate independent review:

- Magnesium production volumes and process types;
- Cover gas with global warming potential (SF_6, HFC-134a, FK 5-1-12, CO_2, etc.) consumption/composition or magnesium production (where factors are used);
- Plant-level QA/QC results (including documentation of sampling, measurement method, and measurement results for plant level data);
- Results of QA/QC conducted by any integrating body (e.g., industry association such as the International Magnesium Association.);
- Calculations and estimation method; and
- Where applicable, a list of assumptions in allocating national SF_6 usage, HFC-134a, FK 5-1-12 or other cover gases of interest or production to plant level.

Inventory compilers should determine if national or international measurement standards were used for reporting of global warming cover gas (SF_6, HFC-134a, FK 5-1-12, etc.) consumption or magnesium production data at the individual plants. If standard methods and QA/QC procedures were not followed, then use of these activity data should be reconsidered.

Review of national activity data

QA/QC activities associated with the reference to magnesium production data should be evaluated and referenced. Inventory compilers should check if the trade association or agency that compiled the national production data used acceptable QA/QC procedures. If the QA/QC procedures are deemed acceptable, inventory compilers should reference the QC activity as part of the QA/QC documentation.

Assessment of emission factors

Where company/country-specific factors are used, inventory compilers should review the level of QC associated with the underlying data. It is *good practice* that the inventory compiler cross-check national level default factors against plant-level factors to determine if these are representative.

Peer review

Inventory compilers should involve magnesium industry experts in a thorough review of the inventory estimate, giving consideration to potential confidentiality issues. Historical production data may be less sensitive to public disclosure than current data and could be utilised for an external peer review of plant level emissions.

Verification of SF_6 emissions data

Inventory compilers should sum the amount of SF_6 used by different industrial sectors (e.g., magnesium, electrical equipment) and compare this value with the total usage of SF_6 in the country, obtained from import/export and production data. This provides an upper bound on the potential emissions.[16]

4.5.4.2 REPORTING AND DOCUMENTATION

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Volume 1, Section 6.11. 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 estimates from the magnesium source category separately by industry segments such as primary production, secondary production and casting.

The following additional information can provide a reasonable degree of transparency in reporting:

Direct reporting

- Number of magnesium plants reporting;
- The types of processes and manufacture employed;
- Magnesium and magnesium products produced;
- SF_6 emissions associated with the magnesium segment;
- Use of other protective cover gases with global warming potential; and
- Emission factor data (and reference) for each protective cover gas with global warming potential.

National cover gas sales-based estimate of potential emissions

- National SF_6 consumption (and reference);
- National use of HFC-134a assigned to the magnesium sector;
- National use of FK 5-1-12 assigned to the magnesium sector;
- Assumptions for allocating SF_6 , HFC-134a, FK 5-1-12, used to magnesium;
- Estimate of percentage of national SF_6, HFC-134a, FK 5-1-12, used in magnesium (and reference); and
- Any other assumptions made.

In most countries, the magnesium industry will be represented by a small number of plants. In this industry, the activity level data and cover gas emissions (that are directly related to activity levels) may be considered confidential business information and public reporting may be subject to confidentiality considerations.

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[16] It may not always be the case that such aggregated consumption data will provide an upper limit on emissions. It is possible, depending on the national characteristics of the SF_6 consuming industry that in some years actual emissions of SF_6 may be greater than consumption of SF_6. For instance, consumption in die casting of magnesium may be very low, there may not be much semiconductor manufacturing, but a considerable bank of SF_6 in electrical equipment may have evolved through the years. In this case, leakage from bank combined with emissions resulting from decommissioning of equipment may lead to actual emissions that exceed consumption of SF_6 (potential emissions). See also Section 8.2 on SF_6 emissions from electrical equipment.

4.6 LEAD PRODUCTION

4.6.1 Introduction

PRIMARY PRODUCTION PROCESSES

There are two primary processes for the production of rough lead bullion from lead concentrates. The first type is sintering/smelting, which consists of sequential sintering and smelting steps and constitutes roughly 78 percent of the primary lead production. The second type is direct smelting, which eliminates the sintering step and constitutes the remaining 22 percent of primary lead production in the developed world. (Sjardin, 2003)

In the sintering/smelting process, the initial sintering blends lead concentrates with recycled sinter, lime rock and silica, oxygen, and high-lead-content sludge to remove sulphur and volatile metals via combustion (Metallurgical Industry, 1995). The process, which produces a sinter roast that consists of lead oxide and other metallic oxides, results in the emission of sulphur dioxide (SO_2) and energy-related carbon dioxide (CO_2) from the natural gas used to ignite the lead oxides (DOE, 2002). The sinter roast is then put in a blast furnace along with ores containing other metals, air, smelter by-products, and metallurgical coke (Metallurgical Industry, 1995). The coke burns as it reacts with air and produces carbon monoxide (CO) that actually performs the reduction of the lead oxide by chemical reaction (DOE, 2002). The smelting process occurs in either a traditional blast furnace or an Imperial Smelting Furnace, and it is the reduction of the lead oxide during this process that produces CO_2 emissions (Sjardin, 2003). The sintering process produces molten lead bullion (Metallurgical Industry, 1995).

In the direct smelting process, the sintering step is skipped, and the lead concentrates and other materials are entered directly into a furnace in which they are melted and oxidized (Sjardin, 2003). A variety of furnaces are used for the direct smelting process, with the Isasmelt-Ausmelt, Queneau-Schumann-Lurgi, and Kaldo furnaces used for bath smelting and the Kivcet furnace used for flash smelting. A number of reducing agents, which include coal, metallurgical coke, and natural gas, are used in the process in different quantities for each furnace, which results in different levels of CO_2 emissions for each type of furnace (Sjardin, 2003; LDA, 2002). The direct smelting process offers significant environmental and potential cost saving benefits through the avoidance of the sintering process and is therefore expected to constitute a growing portion of primary refinery lead production in the future (LDA, 2002).

SECONDARY PRODUCTION PROCESS

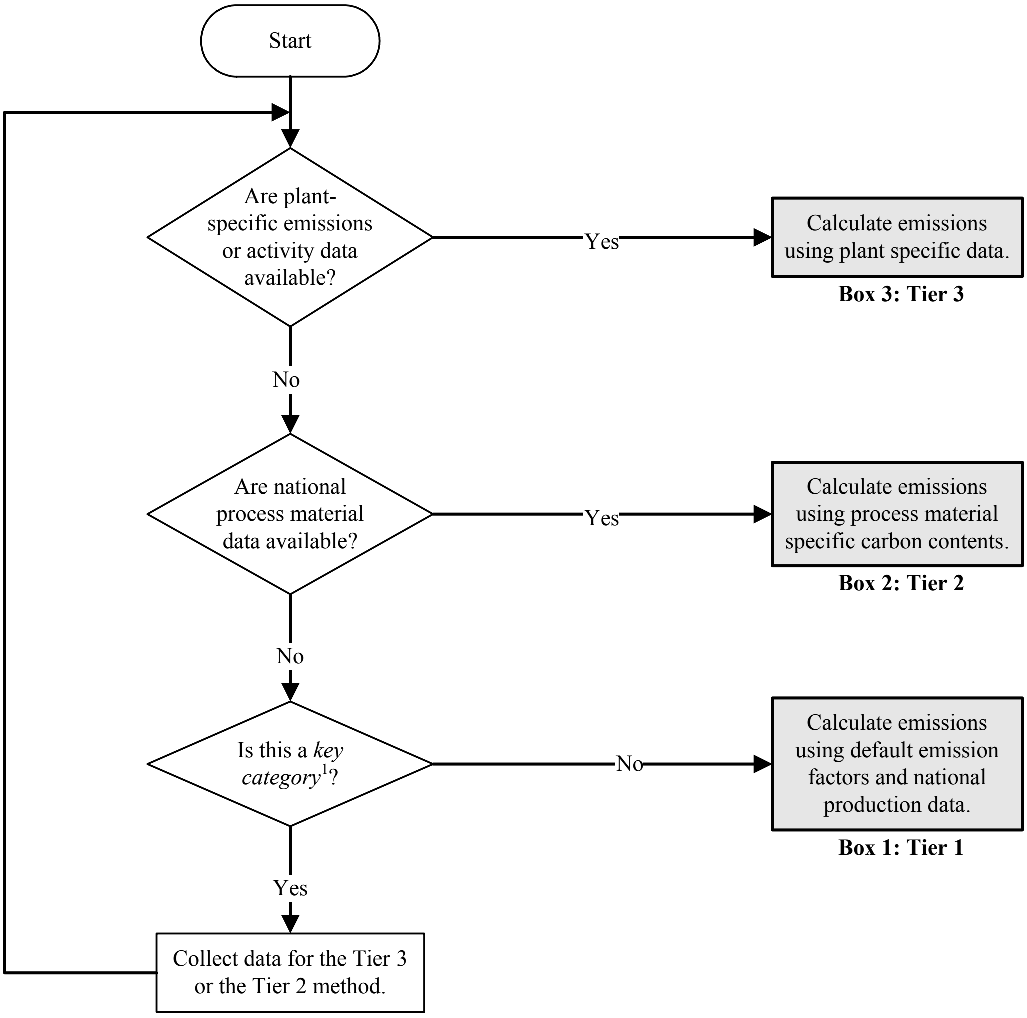
The secondary production of refined lead amounts to the processing of recycled lead to prepare it for reuse. The vast majority of this recycled lead comes from scrapped lead acid batteries. The lead acid batteries are either crushed using a hammer mill and entered into the smelting process with or without desulphurization or they are smelted whole (Sjardin, 2003). Traditional blast furnaces, Imperial Smelting Furnaces, electric arc furnaces, electric resistance furnaces, reverbatory furnaces, Isasmelt furnaces, Queneau-Schumann-Lurgi furnaces, and Kivcet furnaces can all be used for the smelting of these batteries and other recycled scrap lead (Sjardin, 2003). As with the furnaces used for primary lead bullion production, these furnaces generate different levels of CO_2 emissions from their use of differing types and quantities of reductants. The primary reductants are coal, natural gas, and metallurgical coke, although the electric resistance furnace uses petroleum coke (Sjardin, 2003).

4.6.2 Methodological Issues

4.6.2.1 CHOICE OF METHOD

The *IPCC Guidelines* outline three methods for calculating CO_2 emissions from lead production. The choice of a *good practice* method depends on national circumstances as shown in the decision tree in Figure 4.15. The Tier 1 method calculates emissions from general emission factors applied to a country's total lead production and is the least accurate. This method is appropriate only when lead production is not a *key category*. The Tier 2 method uses country specific process material data for both primary and secondary production processes multiplied by the appropriate carbon contents of process materials. The Tier 3 method requires facility-specific measured activity or emissions data.

Figure 4.15 Decision tree for estimation of CO_2 emissions from lead 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 1 METHOD

The simplest estimation method is to multiply default emission factors by lead production. When the only data available are national lead production statistics, it is *good practice* to use default emission factors. Equation 4.32 calculates total carbon dioxide emissions from lead production by summing emissions by source and accounting for emissions from secondary feedstock pre-treatment. If it is not possible to differentiate the type of production process, the default emission factor should be used. The default emission factor assumes a that 80 percent of production (including both primary and secondary) is smelted using an Imperial Smelting Furnaces or blast furnaces, while the remaining 20 percent is smelted using the direct smelting method in the Kivcet, Ausmelt, and Queneau-Schumann-Lurgi furnaces. This assumption is consistent with global lead production data (Sjardin, 2003).

EQUATION 4.32
CO_2 EMISSIONS FROM LEAD PRODUCTION

$$E_{CO2} = DS \bullet EF_{DS} + ISF \bullet EF_{ISF} + S \bullet EF_S$$

Where:

E_{CO2} = CO_2 emissions from lead production, tonnes

DS = quantity of lead produced by Direct Smelting, tonnes

EF_{DS} = emission factor for Direct Smelting, tonne CO_2/tonne lead product

ISF = quantity of lead produced from the Imperial Smelting Furnace, tonnes

EF_{ISF} = emission factor for Imperial Smelting Furnace, tonne CO_2/tonne lead product

S = quantity of lead produced from secondary materials, tonnes

EF_S = emission factor for secondary materials, tonne CO_2/tonne lead product

The CO_2 emission factors used in Equation 4.32 are shown in Table 4.21.

TIER 2 METHOD

The Tier 2 method recognizes that there are substantial differences in carbon dioxide emissions for lead production depending on the production methodology and the source of the raw materials, either from secondary sources such as recycled batteries, or, from primary production from ores. Secondary lead sources may be pre-treated to remove impurities resulting in carbon dioxide emissions. Emissions can be calculated using country specific emission factors based on the use of reducing agents, furnace types and other process materials of interest. Factors can be developed based on carbon contents applicable to those materials. Table 4.22 provides carbon contents that can be used to derive country-specific factors. These data may be available from governmental agencies responsible for manufacturing or energy statistics, business or industry trade associations, or individual lead companies. Tier 2 is more accurate than Tier 1 because it takes into account the materials and the variety of furnace types used in the lead sector that contribute to CO_2 emissions for a particular country rather than assuming worldwide industry-wide practices.

TIER 3 METHOD

If actual directly measured CO_2 emissions data are available from lead facilities, these data can be aggregated and used directly to account for national emissions using the Tier 3 method. Total national emissions will equal the sum of emissions reported from each facility. If facility emissions are not available, emissions should be calculated from plant-specific data for individual reducing agents and other process materials. To achieve a higher level of accuracy than Tier 2, it is *good practice* to develop emissions estimates at the plant-level because plants can differ substantially in their technology, specifically furnace technology. These data may be available from governmental agencies responsible for manufacturing or energy statistics, or from business or industry trade associations, but is preferably aggregated from data furnished by individual lead facilities.

4.6.2.2 CHOICE OF EMISSION FACTORS

TIER 1 METHOD

When the only data available are national lead production statistics, it is *good practice* to use default emission factor of 0.52 tonne of CO_2/ tonne of lead (Sjardin 2003). This default should only be used when no information is available on the relative amounts of lead produced from primary and from secondary materials. If information is available, emissions should be calculated using the appropriate factors in Table 4.21. (Sjardin, 2003). The uncertainty in the default factor is high and varies depending on the mix of production methods and the percentage of secondary processing. In addition, the factor assumes that 80 percent of the world's lead production (including both primary and secondary) is smelted using an Imperial Smelting Furnaces, while the remaining 20 percent is smelted using the direct smelting method in the Kivcet, Ausmelt, and Queneau-Schumann-Lurgi furnaces (Sjardin, 2003).

TABLE 4.21
GENERIC CO_2 EMISSION FACTORS FOR LEAD PRODUCTION BY SOURCE AND FURNACE TYPE
(tonnes CO_2/tonne product)

From Imperial Smelt Furnace (ISF) Production	From Direct Smelting (DS) Production	From Treatment of Secondary Raw Materials	Default Emission Factor (80% ISF, 20% DS)
0.59	0.25	0.2	0.52
Source: Sjardin (2003)			

TIER 2 METHOD

This method offers the opportunity to adjust emission factors to reflect variations from the presumed norms based on plant-specific data for the carbon content of these materials and based on furnace type. The default carbon contents in Table 4.22 should be used if an inventory compiler does not have information on conditions in lead facilities, but has detailed activity data for the process materials. The default values in Table 4.22 are derived from the default values in Tables 1.2 and 1.3 in Volume 2, Chapter 1 and should be referenced for further information.

TABLE 4.22
MATERIAL-SPECIFIC CARBON CONTENT FOR LEAD PRODUCTION (kg carbon/kg)

Process Materials	**Carbon Content**
Blast Furnace Gas	0.17
Charcoal*	0.91
Coal[1]	0.67
Coal Tar	0.62
Coke	0.83
Coke Oven Gas	0.47
Coking Coal	0.73
EAF Carbon Electrodes[2]	0.82
EAF Charge Carbon[3]	0.83
Fuel Oil[4]	0.86
Gas Coke	0.83
Natural Gas	0.73
Petroleum Coke	0.87

Source: References for carbon content data are included in Table 1.2 and 1.3 in Volume 2, Chapter 1.

Notes:

[1] Assumed other bituminous coal

[2] Assumed 80 percent petroleum coke and 20 percent coal tar

[3] Assumed coke oven coke

[4] Assumed gas/diesel fuel

* 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.)

TIER 3 METHOD

The Tier 3 method is based on aggregated emission estimates or the application of the Tier 2 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 4.22. While Table 4.22 provides default carbon contents, it is *good practice* under Tier 3 to adjust these values to reflect variations at the plant level from default values represented in the table. The default factors listed in Table 4.22 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 4.22 would not be applied to the Tier 3 method in most instances.

4.6.2.3 CHOICE OF ACTIVITY DATA

TIER 1 METHOD

The Tier 1 method requires only the amount of lead produced in the country and if available, the amount produced by furnace type. These data may be available from governmental agencies responsible for manufacturing statistics, business or industry trade associations, or individual lead companies. These tonnages can then be multiplied by the corresponding emission factor in Table 4.21 to estimate CO_2 emissions from the sector or the default factor if furnace type is unavailable.

TIER 2 METHOD

The Tier 2 method requires only the total amounts of reducing agents and other process materials used for lead production in the country. These data may be available from governmental agencies responsible for manufacturing or energy statistics, business or industry trade associations, or individual lead companies. These amounts can then be multiplied by the appropriate carbon contents in Table 4.22 and summed to determine total CO_2 emission from the sector. However, activity data collected at the plant-level is preferred (Tier 3). If this is not a *key category* and data for total industry-wide reducing agents and process materials are not available, emissions can be estimated using the Tier 1 approach.

TIER 3 METHOD

The Tier 3 method requires collection, compilation, and aggregation of facility-specific measured emissions or activity data. If emissions data are not available, the Tier 3 method requires activity data to be collected at the plant level and aggregated for the sector. The amounts of reducing agents and the type of furnace used are more accurately determined in this manner. These data may be available from governmental agencies responsible for manufacturing or energy statistics, or from business or industry trade associations, but are preferably aggregated from data furnished by individual lead facilities. This approach also allows for additional accuracy by allowing individual companies to provide more accurate plant-specific data and/or to use more relevant emission factors to reflect carbon contents and furnace types that may differ from the default factors used in the Tier 2 method.

4.6.2.4 COMPLETENESS

In estimating emissions from this source category, there is a risk of double counting or omission in either the IPPU or the Energy Sector. As a general guide, all process emissions from lead production should be reported in the IPPU Sector.

4.6.2.5 DEVELOPING A CONSISTENT TIME SERIES

Emissions from lead production should be calculated using the same method for every year in the time series. Where data are unavailable to support a Tier 3 method for all years in the time series, these gaps should be recalculated according to the guidance provided in Volume 1, Chapter 5, Time Series Consistency and Recalculation.

4.6.3 Uncertainty assessment

Uncertainty estimates for lead production result predominantly from uncertainties associated with activity data, and from uncertainty related to the emission factor. Table 4.23 provides an overview of the uncertainties for emission factors and activity data.

4.6.3.1 EMISSION FACTOR UNCERTAINTIES

The default emission factors used in Tier 1 may have an uncertainty of ± 50 percent. Tier 2 carbon contents are expected to have an uncertainty of ± 15 percent. Tier 3 unit specific emission factors would be expected to be within 5 percent if plant-specific carbon content data are available.

4.6.3.2 ACTIVITY DATA UNCERTAINTIES

National production 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 lead production would likely be within 10 percent. Tier 3 requires plant-specific information on production data (about 5 percent uncertainty). In addition, actual emissions data for tier 3 would be expected to have ± 5 percent uncertainty.

TABLE 4.23
UNCERTAINTY RANGES

Method	Data Source	Uncertainty Range
Tier 1	National Production Data	± 10%
	Default Emission Factor	± 50%
	Emission Factors by Process Type	± 20%
Tier 2	Amounts and Types of Reducing Agents Used	± 10%
	Process Material Carbon Contents	± 15%
Tier 3	Facility-Derived = Process Materials Data	± 5%
	Facility-Specific Measured CO_2 Data	± 5%
	Facility-Specific Emission Factors	± 5%

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

4.6.4.1 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Volume 1, Chapter 6, and an expert review of the emissions estimates. Additional quality control checks as outlined in Volume 1, Chapter 6, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventories agencies are encouraged to use higher tier QA/QC for *key categories* as identified in Volume 1, Chapter 4.

In addition to the guidance in Volume 1, Chapter 6, specific procedures of relevance to this source category are outlined below.

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.

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 lead production, inventory compilers should compare plant data with other plants.

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 is in place at most sites, then the uncertainty of the emissions estimates may be revised downwards.

Expert review

Inventory compilers should include key industrial trade organisations associated with lead production in a review process. This process should begin early in the inventory development process to provide input to the development and review of methods and data acquisition

Third party reviews are also useful for this source category, particularly related to initial data collection, measurement work, transcription, calculation and documentation.

Activity data check

For all tier levels, inventory compilers should check with Volume 2: Energy to ensure that emissions from reducing agents and process materials (coal, coke, natural gas, etc.) are not double-counted or omitted.

Inventory compilers should examine any inconsistency between data from different plants to establish whether these reflect errors, different measurement techniques or result from real differences in emissions, operational conditions or technology. This is particularly relevant to the plant-specific estimates of amounts of reducing agents or reported carbon content of process materials.

Inventory compilers should compare aggregated plant-level estimates to industry totals for process materials consumption where such trade data are available.

4.6.4.2 REPORTING AND DOCUMENTATION

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

TIER 1 METHOD

Besides reporting of estimated emissions, it is *good practice* to report the total lead production by process and corresponding emission factors used.

TIER 2 METHOD

Good practice is to document the estimated or calculated emissions, all activity data, and corresponding carbon contents any assumptions or data justifying alternative values. There should be a clear explanation of the linkage with the Volume 2, Energy, to demonstrate that double counting or missing emissions have not occurred.

TIER 3 METHOD

Good practice is to document the calculated emissions and source of all data, taking into account the need to protect the confidentiality of data for specific facilities if the data are business-sensitive or of a proprietary nature. In addition, inventory compilers should for all tiers, document all information needed to reproduce the estimate, as well as the QA/QC procedures.

4.7 ZINC PRODUCTION

4.7.1 Introduction

PRIMARY PRODUCTION PROCESSES

There are three different types of primary zinc production. The first method is a metallurgical process called electro-thermic distillation. The process is used to combine roasted concentrate and secondary zinc products into a sinter feed that is burned to remove zinc, halides, cadmium, and other impurities. The resulting zinc oxide-rich sinter is combined with metallurgical coke in an electric retort furnace that reduces the zinc oxides and produces vaporized zinc which is captured in a vacuum condenser. The reduction results in the release of non-energy carbon dioxide (CO_2) emissions. The electro-thermic distillation process is used in the United State and in Japan. (Sjardin, 2003; European IPPC Bureau, 2001)

The second method of zinc production is a pyrometallurgical process involving the use of an Imperial Smelting Furnace, which allows for the simultaneous treatment of lead and zinc concentrates. The process results in the simultaneous production of lead and zinc and the release of non-energy CO_2 emissions. The metallurgical coke/coal reductant used in this process must be allocated to lead and zinc production in order to perform an emission calculation without double counting. A mass based allocation results in a factor of 0.74 tonnes coke/tonne zinc. (Sjardin, 2003; European IPPC Bureau, 2001)

The third zinc production method is the electrolytic process, which is a hydrometallurgical technique. In this process, zinc sulphide is calcined, resulting in the production of zinc oxide. The zinc oxide is then leached in sulphuric acid and purified to remove iron impurities, copper, and cadmium. The zinc is then drawn out of the solution using electrolysis. The electrolytic process does not result in non-energy CO_2 emissions. (Sjardin 2003; European IPPC Bureau 2001)

SECONDARY PRODUCTION PROCESSES

There are more than 40 hydrometallurgical and pyrometallurgical technologies that can be used to recover zinc metal from various materials. The preferred method for a given situation depends on the zinc source (contamination level and zinc concentration) and the desired end use for the recovered zinc. The process frequently consists of zinc concentration (through physical and/or chemical separation), sintering, smelting, and refining. In some cases, high grade zinc is removed from this process after physical concentration and consumed by other industries, including iron and steel manufacture, brass manufacture, and zinc die-casting, without going through the rest of the process steps. (Sjardin, 2003)

The sintering, smelting, and refining steps are identical to the steps used in the primary zinc production process, so certain smelting processes are considered emissive, while the sintering and refining steps are considered non emissive from the perspective of non-energy CO_2 emissions. When the concentration step involves the use of a carbon-containing reductant and high temperatures to volatilize or fume zinc from the source materials, the process could result in non-energy CO_2 emissions. The Waelz Kiln and slag reduction or fuming processes are two such concentration methods. The Waelz Kiln process, which is used to concentrate zinc in flue dusts, sludges, slags, and other zinc-containing materials, involves the use of metallurgical coke as a reductant. However, the reduced zinc is re-oxided during the processes and the metallurgical coke also serves as a heat source during the process. The slag reduction or fuming process, which is used strictly to concentrate zinc in molten slags from copper and zinc smelting, involves the use of coal or another carbon source as a reductant. (Sjardin, 2003; European IPPC Bureau, 2001)

4.7.2 Methodological issues

4.7.2.1 CHOICE OF METHOD

The *IPCC Guidelines* outline several approaches for calculating CO_2 emissions from zinc production. The choice of a *good practice* method depends on national circumstances as shown in the decision tree in Figure 4.16. The Tier 3 method may be used if facility-specific measured emissions data are available. Tier 2 method uses country specific emissions factors for both primary and secondary production processes. The Tier 1 method is very simple and it may lead to errors due to its reliance on assumptions rather than actual data. The Tier 1 method calculates emissions from general emission factors applied to a country's total zinc production and is the least rigorous method. This method should only be used when zinc production is not a *key category*.

TIER 1 METHOD

The simplest estimation method is to multiply default emission factors by zinc product type (Equation 4.33). When the only data available are national zinc production statistics, it is *good practice* to use default emission factors. If material specific data are not available to calculate emissions using the Tier 2 methodology, but the process type is known, inventory compilers can calculate emissions using Equation 4.34.

EQUATION 4.33
CO_2 EMISSIONS FROM ZINC PRODUCTION (TIER 1)

$$E_{CO2} = Zn \bullet EF_{default}$$

Where:

E_{CO2} = CO_2 emissions from zinc production, tonnes

Zn = quantity of zinc produced, tonnes

$EF_{default}$ = default emission factor, tonnes CO_2/tonne zinc produced

EQUATION 4.34
CO_2 EMISSIONS FROM ZINC PRODUCTION (TIER 1)

$$E_{CO2} = ET \bullet EF_{ET} + PM \bullet EF_{PM} + WK \bullet EF_{WK}$$

Where:

E_{CO2} = CO_2 emissions from zinc production, tonnes

ET= quantity of zinc produced by electro-thermic distillation, tonnes

EF_{ET} = emission factor for electro-thermic distillation, tonnes CO_2/tonne zinc produced

PM = quantity of zinc produced by pyrometallurgical process (Imperial Smelting Furnace Process) , tonnes

EF_{PM} = emission factor for pyrometallurgical process, tonnes CO_2/tonne zinc produced

WK = quantity of zinc produced by Waelz Kiln process, tonnes

EF_{WK} = emission factor for Waelz Kiln process, tonnes CO_2/tonne zinc produced

TIER 2 METHOD

Emission can be calculated using country specific emission factor based on aggregated plant statistics on the use of reducing agents, furnace types and other process materials of interest is developed based on default emission factors applicable to those materials. These data may be available from governmental agencies responsible for manufacturing or energy statistics, business or industry trade associations, or individual zinc companies. Tier 2 is more accurate than Tier 1 because it takes into account the materials and the variety of furnace types used in the zinc sector that contribute to CO_2 emissions for a particular country rather than assuming industry-wide practices.

TIER 3 METHOD

If actual measured CO_2 emissions data are available from zinc facilities, these data can be aggregated and used directly to account for national emissions using the Tier 3 method.

4.7.2.2 CHOICE OF EMISSION FACTORS

TIER 1 METHOD

The emission factor for the pyrometallurgaical process (Imperial Smelting Furnace) is an aggregate, weighted emission factor encompassing both primary and secondary zinc production in Europe (Sjardin, 2003), No data was available to determine an emission factor for the electro-thermic process. An emission factor based on the amount of coke consumed per tonne of EAF dust consumed in a Waelz Kiln furnace was developed based on the materials balance provided by Viklund-White (2000), wherein Viklund-White finds that 400 kg of coke are consumed for every metric tonne of EAF dust consumed.

TABLE 4.24
TIER 1 CO_2 EMISSION FACTORS FOR ZINC PRODUCTION

Process	Emission Factor	Source
Waelz Kiln (tonne of CO_2/ tonne zinc)	3.66	Derived from Viklund-White C. (2000) The Use of LCA for the Environmental Evaluation of the Recycling of Galvanized Steel. ISIJ International. Volume 40 No. 3: 292-299.
Pyrometeallurgical (Imperial Smelting Furnace) (tonne of CO_2/ tonne zinc)	0.43	Sjardin 2003. CO_2 Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry. Copernicus Institute, Utrecht, The Netherlands. June 2003.
Electro-thermic	Unknown	
Default Factor (tonne of CO_2/ tonne zinc)	1.72	default factor is based on weighting of known emission factors (60% Imperial Smelting, 40% Waelz Kiln)

TIER 2 METHOD

The Tier 2 method requires the calculation of a country specific emission factor based on the total amount of reducing agents and other carbon containing process materials used for zinc production in the country. These country specific emission factors should be based on aggregated plant statistics on the use of reducing agents, furnace types and other process materials of interest. An emission factor was developed based on the amount of metallurgical coke consumed per tonne of EAF dust consumed: 0.4 tonnes coke/ tonne EAF dust consumed (Viklund-White, 2000). If activity data are available, an emission factor of 1.23 tonnes of EAF dust per tonne of zinc could be used to calculate emissions. When producing zinc from EAF dust in a Waelz Kiln furnace, the complexities of the process suggest that emission factors are more accurate if they are based on the amount of EAF dust consumed rather than the total zinc produced . This is because the amount of reduction materials (metallurgical coke) consumed is directly dependent upon the amount, and zinc content, of the EAF dust consumed. Weighing equipment is used in the Waelz Kiln process to control the amount of metallurgical coke entered into the kiln (Sjardin 2003; European IPPC Bureau 2001).

4.7.2.3 CHOICE OF ACTIVITY DATA

TIER 1 METHOD

The Tier 1 method requires only the amount of zinc produced in the country, and if available, the process type. These data may be available from governmental agencies responsible for manufacturing statistics, business or industry trade associations, or individual zinc companies. These tonnages can then be multiplied by the default emission factors to estimate CO_2 emissions.

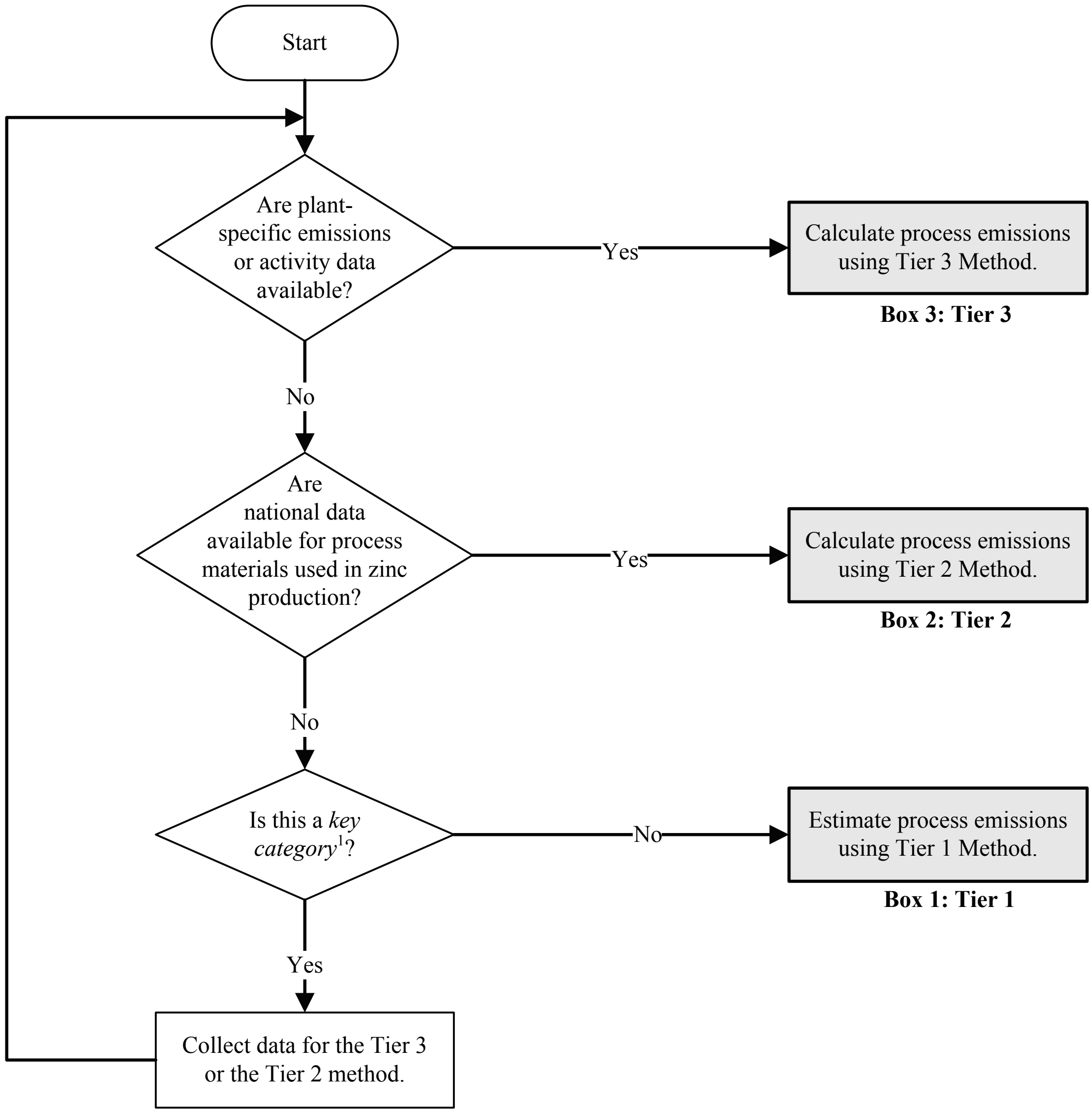
TIER 2 METHOD

The Tier 2 method requires the calculation of a country specific emission factor based on the total amount of reducing agents and other carbon containing process materials used for zinc production in the country. These data may be available from governmental agencies responsible for manufacturing or energy statistics, business or industry trade associations, or individual zinc companies. These country specific emission factors can then be multiplied by the production amount to determine total CO_2 emission from the sector. 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.

TIER 3 METHOD

The Tier 3 method requires collection, compilation, and aggregation of facility-specific measured emissions data, if any. However, activity data collected at the plant-level can also be used, with separate emission factors for each plant multiplied by plant specific production. 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.

Figure 4.16 Decision tree for estimation of CO_2 emissions from zinc 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.

4.7.2.4 COMPLETENESS

In estimating emissions from this source category, there is a risk of double-counting or omission in either the Industrial Processes or the Energy Sector. It is important to note that the Tier 1 emission factor assumes that the CO_2 emissions from the combustion of various fuels used for production of heat in the calcining, sintering, leaching, purification smelting, and refining processes are captured within the CO_2 from fossil fuel combustion emission category. In using the tier 2 or 3 methodologies, double-counting can be avoided. The largest source of potential double-counting, emissions from coke production, are calculated in Section 4.2 and reported in the Energy Sector.

4.7.2.5 DEVELOPING A CONSISTENT TIME SERIES

Emissions from zinc production should be calculated using the same method for every year in the time series. Where data are unavailable to support a Tier 3 method for all years in the time series, these gaps should be recalculated according to the guidance provided in Volume 1, General Guidance and Reporting.

4.7.3 Uncertainty assessment

Uncertainty estimates for zinc production result predominantly from uncertainties associated with activity data, and from uncertainty related to the emission factors. Table 4.25 provides an overview of the uncertainties for emission factors and activity data.

4.7.3.1 EMISSION FACTOR UNCERTAINTIES

The default emission factors used in Tier 1 may have an uncertainty of ± 50 percent. Tier 2 country specific emission factors are expected to have an uncertainty of ± 15 percent. Tier 3 unit specific emission factors would be expected to be within 5 percent if plant-specific carbon content data are available.

4.7.3.2 ACTIVITY DATA UNCERTAINTIES

National production 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 lead production would likely be within 10 percent. Tier 3 actual emissions data would be expected to have ± 5 percent uncertainty.

TABLE 4.25
UNCERTAINTY RANGES

Method	Data Source	Uncertainty Range
Tier 1	National Production Data Default Emission Factors Process Specific Emission Factors	± 10% ± 50% ± 20%
Tier 2	National Reducing Agent & Process Materials Data Country Specific Emission Factors	± 10% ± 15%
Tier 3	Facility-Derived = Process Materials Data Facility-Specific Measured CO_2 Data Facility-Specific Emission Factors	± 5% ± 5% ± 5%

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

4.7.4.1 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Volume 1, Chapter 6, and an expert review of the emissions estimates. In addition to the guidance in Volume 1, specific procedures of relevance to this source category are outlined below.

Review of emission factors

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

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 zinc production, inventory compilers should compare plant data with other plants.

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 is in place at most sites, then the uncertainty of the emissions estimates may be revised downwards.

Expert review

Inventory compilers should include key industrial trade organisations associated with zinc production in a review process. This process should begin early in the inventory development process to provide input to the development and review of methods and data acquisition.

Third party reviews are also useful for this source category, particularly related to initial data collection, measurement work, transcription, calculation and documentation.

Activity data check

For all tier levels, inventory compilers should check to ensure that emissions from reducing agents and process materials (coal, coke, natural gas, etc.) are not double-counted as energy related emissions or omitted.

Inventory compilers should examine any inconsistency between data from different plants to establish whether these reflect errors, different measurement techniques or result from real differences in emissions, operational conditions or technology. This is particularly relevant to the plant-specific estimates of amounts of reducing agents or reported carbon content of process materials.

Inventory compilers should compare aggregated plant-level estimates to industry totals for process materials consumption where such trade data are available.

4.7.4.2 REPORTING AND DOCUMENTATION

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

TIER 1 METHOD

Besides reporting of estimated emissions, it is *good practice* to report the total zinc production by process and corresponding emission factors used.

TIER 2 METHOD

Good practice is to document the estimated or calculated emissions, all activity data, and corresponding emission factors and any assumptions or data justifying alternative emission factors.

TIER 3 METHOD

Good practice is to document the calculated emissions and source of all data, taking into account the need to protect the confidentiality of data for specific facilities if the data are business-sensitive or of a proprietary nature. In addition, inventory compilers should for all tiers, document all information needed to reproduce the estimate, as well as the QA/QC procedures

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/EMEPCORINAIR4/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.

SECTION 4.3

FFF (2000). The Norwegian Ferroalloy Producers Research Association, "Emission factors standardized at meeting", Oslo 2000.

IPCC (1997). Revised 1996 IPCC Guidelines for National Greenhouse Inventories. Houghton J.T., Meira Filho L.G., Lim B., Tréanton K., Mamaty I., Bonduki Y., Griggs D.J. Callander B.A. (Eds). Intergovernmental Panel on Climate Change (IPCC), IPCC/OECD/IEA, Paris, France.

IPCC (2000). Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Penman J., Kruger D., Galbally I., Hiraishi T., Nyenzi B., Emmanuel S., Buendia L., Hoppaus R., Martinsen T., Meijer J., Miwa K., Tanabe K. (Eds). Intergovernmental Panel on Climate Change (IPCC), IPCC/OECD/IEA/IGES, Hayama, Japan.

Lindstad, T. (2004). 'CO_2 Emissions from the Production of Silicon Alloys', STF80A04019, SINTEF, Trondheim 2004.

Olsen, S.E., Monsen, B.E. and Lindstad, T. (1998). 'CO_2 Emissions from the Production of Manganese and Chrome Alloys in Norway', Electric Furnace Conference Proceedings Vol. 56, Iron & Steel Society, Warrendale PA 1998, pp 363-369.

Olsen, S.E. (2004). 'CO_2 Emissions from the Production of Manganese Alloys in Norway', STF80A04010, SINTEF, Trondheim 2004.

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.

SECTION 4.5

Bartos, S., Kantamaneni, R., Marks, J. and Laush, C. (2003). "Measured SF_6 Emissions from Magnesium Die Casting Operations," Magnesium Technology 2003, Proceedings of The Minerals, Metals & Materials Society (TMS) Conference, March 2003.

Gjestland, H. and Magers, D. (1996). "Practical usage of sulphur hexafluoride for melt protection in the magnesium die casting industry" Proceedings of the 53rd International Magnesium Conference, 1996, Ube City, Japan

IPCC (2001). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Milbrath, D. (2002). "Development of 3M™ Novec™ 612 Magnesium Protection Fluid as a Substitute for SF_6 Over Molten Magnesium," International Conference on SF_6 and the Environment: Emission Reduction Technologies, November 21-22, 2002, San Diego, CA.

Tranell, G and Engh, T.A. (2004). "Alternatives to SF_6 for the Magnesium Processor – A Technical, Environmental and Economic Assessment", Proceedings of the 61st Annual International Magnesium Association Conference, May 2004, New Orleans, LA, USA.

SECTION 4.6

DOE (2002). Mining Industry of the Future: Energy and Environmental Profile of the U.S. Mining Industry. Prepared by BCS, Inc for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, December 2002.

LDA (2002). Technical Notes: Primary Extraction of Lead., Lead Development Association International. Internet: http://www.ldaint.org/technotes1.htm

Metallurgical Industry (1995). AP 42, Fifth Edition, Volume I, Chapter 12, http://www.epa.gov/ttn/chief/ap42/ch12/index.html

Sjardin, M. (2003). CO_2 Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry. Copernicus Institute, Utrecht, The Netherlands, June 2003.

SECTION 4.7

European IPPC Bureau (2001). Integrated Pollution Prevention and Control (IPPC) Best Available Techniques Reference Document on the Non Ferrous Metals Industries, December 2001. http://eippcb.jrc.es/pages/FActivities.htm

Sjardin, M. (2003). CO_2 Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry. Copernicus Institute, Utrecht, The Netherlands, June 2003.

Viklund-White C. (2000). The Use of LCA for the Environmental Evaluation of the Recycling of Galvanized Steel. *ISIJ International*. Volume 40 No. 3: 292-299.