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Stationary source emissions — Determination of greenhouse gas (GHG) emissions in energy-intensive industries

Part 4: Aluminium industry

National foreword

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European foreword

This document (EN 19694-4:2016) has been prepared by Technical Committee CEN/TC 264 “Air quality”, the secretariat of which is held by DIN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by January 2017, and conflicting national standards shall be withdrawn at the latest by January 2017.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

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EN 19694, *Stationary source emissions — Determination of greenhouse gas (GHG) emissions in energy-intensive industries* is a series of standards that consists of the following parts:

- *Part 1: General aspects*
- *Part 2: Iron and steel industry*
- *Part 3: Cement industry*
- *Part 4: Aluminium industry*
- *Part 5: Lime industry*
- *Part 6: Ferroalloy industry*

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, Former Yugoslav Republic of Macedonia, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

Introduction

This European Standard serves the following purposes:

- measuring, testing and quantifying GHG emissions from the aluminium industry;
- assessing the level of GHG emissions performance of production processes over time, at production sites;
- establishing and providing reliable, accurate and quality information for reporting and verification purposes.

This European Standard can be used to measure, report and compare the GHG emissions of an aluminium production facility. Data for individual facilities, sites or works may be combined to measure, report and compare GHG emissions for a company, corporation or group.

Direct fuel based emissions are not included; for calculation of this part of the GHG emissions, see EN 19694–1.

The European Standard deals with sector-specific aspects for the determination of greenhouse gas (GHG) emissions from aluminium production and is based on documents mentioned under tier 3 of Section 4.4.2.4 of the 2006 IPCC guidelines [6].

1 Scope

This European Standard specifies a harmonized method for calculating the emissions of greenhouse gases from the electrolysis section of primary aluminium smelters and aluminium anode baking plants. It also specifies key performance indicators for the purpose of benchmarking of aluminium. This also defines the boundaries.

NOTE Other requirements and other EU Directives may be applicable to the product(s) falling within the scope of this standard.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 19694-1, *Stationary source emissions — Determination of greenhouse gas (GHG) emissions in energy-intensive industries — Part 1: General aspects*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 19694-1 and the following apply.

3.1
aluminium electrolysis
section of an aluminium primary smelter where aluminium is converted from aluminium oxide to aluminium metal in electrolysis cells

3.2
anode baking plant
production of carbon anodes for use in aluminium prebake electrolysis cells

3.3
PFC gases
gas emitted from aluminium electrolysis consisting of CF_4 and C_2F_6

3.4
grid specific CO_2 factor
CO_2 factor (t CO_2/MWh) associated with the electricity delivered to a specific aluminium smelter from their supplier

4 List of abbreviated terms

AE	Anode effect
CWPB	Centre-Worked prebake
DAE	Direct anode emissions
DEE	Direct electrolysis emissions
GHG	Green House Gas

HSS	Horizontal Stud Søderberg
IPCC	Intergovernmental Panel on Climate Change
PFPB	Point Feeder prebake
SWPB	Side-Worked prebake
TIE	Electrolysis electricity consumption
VSS	Vertical Stud Søderberg
WBCSD	World Business Council for Sustainable Development (WBCSD)
WRI	World Resources Institute

5 Symbols, units and chemical formulae

5.1 Symbols and units

Symbol	**Quantity**	**Unit**
A_{EM}	Anode effects, (= frequency x average duration)	minutes/cell day
A_{EO}	Anode effect overvoltage	millivolts
$\mathrm{A_{NC}}$	Net anode consumption	wt %
A_{sha}	Ash content in baked anodes	wt %
$\mathrm{A_{shp}}$	Ash content in pitch in weight %	wt %
A_{shpc}	Ash content in packing coke, wt %	wt %
B_A	Baked anode production	tonne/year
B_{AW}	Baked anode weight	tonne
C_{BA}	Carbon content of baked anodes,	wt %
C_{Butt}	Carbon content of anode butts	tonne/year
C_E	Current efficiency for aluminium production	%
$\mathrm{C_{SM}}$	Emissions of cyclohexane soluble matter, kilograms per tonnes aluminium	kg/tonne
E_{CF_4}	Emissions of tetrafluoromethane, kg CF_4 per year	kg/year
$E_{C_2F_6}$	Emissions of hexafluoroethane, kg C_2F_6 per year	kg/year
E_{CO_2}	CO_2 emissions in tonnes per year	tonne/year
E_{FPC}	Emission factor of Packing Coke, tCO_2/t of Packing Coke	tonne

Symbol	**Quantity**	**Unit**
$F_{\frac{C_2F_6}{CF_4}}$	Weight fraction of $\frac{C_2F_6}{CF_4}$	dimensionless
G_A	Weight of loaded green anodes = $\left(\frac{\mathrm{G_{AW}}}{\mathrm{B_{AW}}}\right)B_A$	tonne/year
G_{AW}	Green anode weight	tonne
G_{WP}	Global warming potential. Use latest G_{WP} data from IPCC	tonnes CO_2 equivalent/tonne
H_w	Hydrogen content in green anode	wt %
M_{BA}	Total mass of baked anodes	tonne/year
M_{Butt}	Total mass of anode butts	tonne/year
M_P	Tonnes aluminium per year	tonne/year
N_{AC}	Net anode consumption, tonnes per tonnes aluminium	tonne/year
O_{FPC}	Oxidation factor of packing coke (typically 1 for this stream)	dimensionless
O_{VC}	Overvoltage coefficient for CF_4	kg_{CF4}/t_{Al}/mV
P_{C}	Paste consumption, tonnes per tonnes aluminium	tonne
P_{CC}	Packing coke consumed per tonnes of baked anode	tonne
P_{CW}	Packing coke weight	tonne
R_{CF_4}	Emission rates of CF_4, kg per tonne of aluminium produced	kg/tonne
$R_{C_2F_6}$	Emission rates of C_2F_6, kg per tonne of aluminium produced	kg/tonne
S_a	Sulphur content in baked anodes	wt %
S_{CF_4}	Slope coefficient for CF_4, kg CF_4 per tonne aluminium per anode effect minute per cell day	tonne/effect minute/cell day
W_t	Waste tar collected	tonne/year
wt	Weight	kg or tonne

5.2 Chemical formulae

Al	Aluminium
Al_2O_3	Aluminium oxide (Alumina)
C	Carbon
CF_4	Tetrafluoromethane
C_2F_6	Hexafluoroethane

CO	Carbon monoxide
CO_2	Carbon dioxide
$NaAlF_6$	Sodium aluminium hexafluoride (cryolite)
NaF	Sodium fluoride
PFC	Perfluorocarbon

6 Calculation methods – General remarks

6.1 Introduction

This standard shall be used in conjunction with EN 19694-1 which contains generic, overall requirements, definitions and rules applicable to the determination of GHG emissions for all energy-intensive sectors, provides common methodological issues and defines the details for applying the rules. The application of this standard to the sector-specific standards ensures accuracy, precision and reproducibility of the results.

6.2 Calculation methods for process GHG emissions from primary aluminium production

Figure 1 gives sources of process emissions and references to where in the standard calculation methods are described.

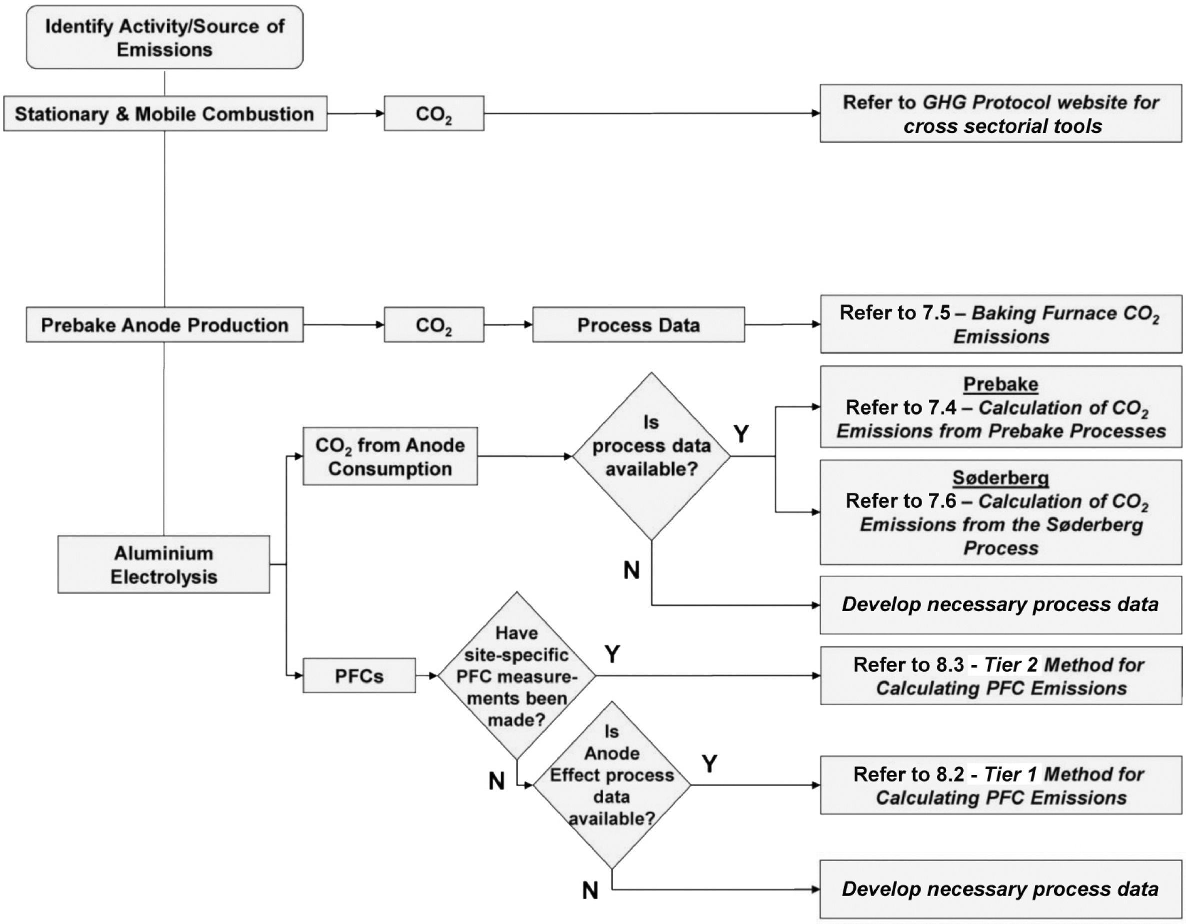

Figure 1 — Decision tree for process carbon dioxide and perfluorocarbon emissions from primary aluminium production

Process CO_2 emissions in state of the art aluminium smelters comprise around 90 % of total direct CO_2 equivalent emissions, with the balance of emissions consisting of CO_2 from fossil fuel combustion and PFC emissions. Guidance on CO_2 emissions from fuel combustion is not included in this document. Methodology for calculating CO_2 emissions from the combustion of fuel in anode baking furnaces is described elsewhere [6, 7], while methodology for calculating process CO_2 emissions is given in Clause 7.

6.3 Sources of carbon dioxide

6.3.1 Electrolysis

Most of the CO_2 emissions result from the electrolytic reaction of the carbon anode with alumina:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2 \tag{1}$$

Carbon dioxide is also emitted during the electrolysis reaction as the carbon anode reacts with other sources of oxygen, primarily from the air. Carbon dioxide is also formed as a result of the Boudouard reaction where CO_2 reacts with the carbon anode forming carbon monoxide, which is then oxidized to form CO_2. Each unit of CO_2 participating in the Boudouard reaction produces two units of CO_2 after air oxidation:

$$CO_2 + C \rightarrow 2CO \tag{2}$$

$$2CO + O_2 \rightarrow 2CO_2 \tag{3}$$

All carbon monoxide formed is assumed to be converted to CO_2. By industry convention no correction is made for the minute amount of carbon consumed as PFCs rather than CO_2 emissions. No CO_2 is produced from cathode consumption unless there is on-site incineration and no recommendation is included here for such operations CO_2 emission from addition of sodium carbonate to electrolyses cells is not included as this is added at infrequent intervals and is an insignificant source.

6.3.2 Anode baking

Another source of CO_2 emissions, specific to prebake technologies, is the baking of green anodes, wherein CO_2 is emitted from the combustion of volatile components from the pitch binder and, for baking furnaces fired with carbon based fuels, from the combustion of the fuel source. Some of the packing coke used to cover the anodes is also oxidized, releasing CO_2 during anode baking.

Carbon dioxide is emitted from the fuel used in the paste plant and the fuel used for firing the anode baking furnace.

6.3.3 Aluminium smelting supporting processes

A further source of carbon dioxide emissions is fuel used in the cast house for heating of the metal during treatment processes before casting, and some fuel may also be used in rodding operations.

6.3.4 Alumina refining

Carbon dioxide is not produced as process emission in the Bayer Process, the process through which alumina is refined from bauxite ore. Most of the emissions associated with alumina refining are from the combustion of fossil fuels, which are covered in the WRI/WBCSD [10] calculation tools for GHG emissions from energy and electricity.

6.4 Sources of PFC

Two perfluorocarbon gases (PFCs), tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6), may be produced during primary aluminium production.

$$4Na_3AlF_6 + 3C \rightarrow 4Al + 12NaF + 3CF_4 \tag{4}$$

$$4Na_3AlF_6 + 4C \rightarrow 4Al + 12NaF + 2C_2F_6 \tag{5}$$

NOTE The following recommendations for calculating PFC emissions are consistent with the inventory guidance of the Intergovernmental Panel on Climate Change (IPCC) [6].

7 Methods for calculation of process carbon dioxide emissions

7.1 General

Direct CO_2 emissions from aluminium production shall be calculated by using one of the following two tiers:

— Tier 1: Process specific equations with industry typical parameters.

— Tier 2: Process specific equations with site or company specific parameters.

NOTE Tier 1 and tier 2 in this standard correspond to what is listed as tier 2 and tier 3 in the IPCC technical guidance [6].

Reference should be made to Figure 1 as an overall guide on how to proceed when calculating direct CO_2 emissions. For calculation of key performance indicator tier 2 shall be used.

7.2 Tier 1 – Method using process specific equations with technology typical parameters for carbon dioxide emissions

Tier 1 method for the calculation of total direct CO_2 emissions shall be based on the calculation of CO_2 emissions from each individual process step which are then summed to calculate total emissions. Equations in 7.4 describe the calculation of CO_2 for prebake technologies, while 7.6 contains the equations for Søderberg technologies.

7.3 Tier 2 – Method using process specific equations with facility specific parameters for carbon dioxide emissions

The most accurate inventories of CO_2 are obtained by using site or company specific data in the equations for calculating emissions (tier 2 method). This data may come from measurements made on site or from data from suppliers. The equations are identical to those used in the tier 1 method described above. However, facility specific or company specific data, rather than technology typical data, shall be used.

7.4 Calculation of carbon dioxide emissions from prebake processes

7.4.1 General

Carbon dioxide emissions resulting from CWPB and SWPB reduction technologies have as their sources electrolysis and anode baking.

7.4.2 Carbon dioxide emissions from prebake anode consumption during electrolysis

The following equation should be used for calculation of CO_2 emissions from prebake anode consumption during electrolysis:

$$E_{CO_2} = \left[M_P \times N_{AC} \left(\frac{100 - S_a - A_{sha}}{100} \right) \right] 3{,}664 \tag{6}$$

where

E_{CO_2} are the CO_2 emissions in tonnes per year;

M_P is the total metal production, tonnes aluminium per year;

N_{AC} is the net anode consumption, tonnes per tonne aluminium;

S_a is the sulphur content in baked anodes, wt %;

A_{sha} is the ash content in baked anodes, wt %;

3,664 is the CO_2 molecular mass: carbon atomic mass ratio, dimensionless.

Parameters used in Formula (6) are defined in Table 2 together with technology typical values for calculating CO_2 emissions from prebake anode consumption during electrolysis.

Alternatively, the following equation may also be used:

$$E_{CO_2} = \left(M_{BA} \times \%C_{BA} - M_{Butts} \times \%C_{Butts}\right)3{,}664 \tag{7}$$

where

E_{CO_2} are the CO_2 emissions in tonnes per year;

M_{BA} is the total mass of baked anodes, tonnes anodes per year;

$\% C_{\mathrm{BA}}$ is the carbon content of baked anodes, wt %;

M_{Butts} is the total mass of anode butts, tonnes anodes per year;

$\% C_{Butts}$ is the arbon content of anode butts, wt %.

Parameters used in Formula (7) are defined in Table 1 together with technology typical values for calculating CO_2 emissions from prebake anode consumption during electrolysis.

Table 1 — Typical uncertainty for individual parameters and analyses used in tier 1 or tier 2 method for carbon dioxide emissions from prebake cells

Parameter	**Tier 1 method**		**Tier 2 method**	
	Data source	**Data uncertainty (± %)**	**Data source**	**Data uncertainty (± %)**
M_P: total metal production (tonnes aluminium per year)	Individual facility records	2	Individual facility records	2
N_{AC}: net anode consumption (tonnes per tonne aluminium)	Individual facility records	5	Individual facility records	5
S_a: sulphur content in baked anodes (wt %)	Use industry typical value, 2	3	Individual facility records	3
A_{sha}: ash content in baked anodes (wt %)	Use industry typical value, 0,4	3	Individual facility records	3
M_{BA} = total mass of baked anodes (tonnes anodes per year)	Individual facility records	2	Individual facility records	2
$\% \ C_{BA}$ = carbon content of baked anodes (wt %)	Use industry typical value, 98	5	Individual facility records	2
M_{Butts} = total mass of anode butts (tonnes anodes per year)	Individual facility records	2	Individual facility records	2
$\% \ C_{Butts}$ = carbon content of anode butts (wt %)	Use industry typical value, 98	5	Individual facility records	2

7.5 Baking furnace carbon dioxide emissions

7.5.1 General

Baking furnace emissions result from three sources:

- combustion of the fuel for firing the furnace;
- combustion of volatile matter released during the baking operation;
- combustion of baking furnace packing material.

7.5.2 Fuel

Carbon dioxide emissions resulting from the fuel consumed during baking furnace firing can be calculated using the WRI/WBCSD [10] calculation tools for GHG emissions from energy and electricity.

7.5.3 Combustion of volatile matter

Calculation of carbon dioxide emissions from pitch volatiles combustion should be calculated according to:

$$E_{CO_2} = \left[G_A - \left(\frac{H_w \times G_A}{100} \right) - B_A - W_T \right] 3{,}664 \qquad (8)$$

where

E_{CO_2}	is the CO_2 emissions in tonnes per year;
G_A	is the weight of loaded green anodes = $\left(\frac{G_{AW}}{B_{AW}} \right) B_A$;
G_{AW}	is the green anode weight, tonnes;
B_{AW}	is the baked anode weight, tonnes;
B_A	is the baked anode production, tonnes baked anode per year;
H_w	is the hydrogen content in green anodes, wt %;
W_T	is the waste tar collected, tonnes;
3,664	is the CO_2 Molecular Mass: Carbon Atomic Mass Ratio, dimensionless.

Parameters included in Formula (8) are defined and industry typical values noted in Table 2.

Alternatively, the following formula may also be used:

$$E_{CO_2} = \left(G_{AW} \times \%C_{GA} - B_{AW} \times \%C_{BA} \right) 3{,}664 \qquad (9)$$

where

E_{CO_2}	is the CO_2 emissions in tonnes per year;
G_{AW}	is the green anodes weight, tonnes;
$\% C_{\mathrm{BA}}$	is the carbon content of green anodes, wt %;
B_{AW}	is the baked anodes weight, tonnes;
% C_{BA}	is the carbon content of baked anodes, wt %.

Table 2 — Typical uncertainty for individual parameters and analyses used in Tier 1 or Tier 2 method for CO_2 emissions from bake furnace pitch volatiles combustion

Parameter	Tier 1 method		Tier 2 method	
	Data Source	**Data uncertainty (± %)**	**Data source**	**Data uncertainty (± %)**
G_{AW}: weight of green anodes (tonnes)	Individual facility records	2	Individual facility records	2
B_{AW}: weight of baked anodes (tonnes)	Individual facility records	2	Individual facility records	2
H_w: hydrogen content in green anodes (wt %)	Use industry typical value, 0,5	5	Individual facility records	5
B_A: baked anode production (tonnes per year)	Individual facility records	2	Individual facility records	2
W_T: waste tar collected (tonnes): a) Riedhammer furnaces b) All other furnaces	Use industry typical value: a) 0,005 x G_A b) Insignificant	20	Individual facility records	20
% C_{GA}: Carbon content of green anodes, wt %	Use industry typical value, 98	5	Individual facility records	2
% C_{BA} = Carbon content of baked anodes, wt %	Use industry typical value, 98	5	Individual facility records	2

7.5.4 Baking furnace packing material

Carbon dioxide emissions from packing coke should be calculated according to:

$$E_{CO_2} = \left[P_{CC} \times B_A \left(\frac{100 - S_{pc} - Ash_{pc}}{100} \right) \right] 3,664 \qquad (10)$$

where

E_{CO_2} are the CO_2 emissions in tonnes per year;

P_{CC} is the packing coke consumed, tonnes per tonne of baked anode;

B_A is the baked anode production, tonnes baked anode per year;

S_{pc} is the sulphur content in packing coke, wt %;

A_{shpc} is the ash content in packing coke, wt %;

3,664 is the CO_2 molecular mass: carbon atomic mass ratio, dimensionless.

Parameters included in Formula (10) are defined and industry typical values noted in Table 3.

Alternatively, by considering packing coke as a fuel, the following formula could be used:

$$E_{co_2} = P_{CW} \times E_{FPC} \times O_{F\,PC} \tag{11}$$

where

E_{CO_2} are the CO_2 emissions in tonnes per year;

P_{CW} is the packing coke weight, tonnes;

E_{FPC} is the emission factor of packing coke, tCO_2/t of packing coke;

O_{FPC} is the oxidation factor of packing coke (typically 1 for this stream).

Table 3 — Typical uncertainty for individual parameters and analyses used in tier 1 or tier 2 method for carbon dioxide emissions from oxidation of bake furnace packing material

Parameter	**Tier 1 method**		**Tier 2 method**	
	Data source	**Data uncertainty (± %)**	**Data source**	**Data uncertainty (± %)**
P_{CC}: packing coke consumption (tonnes per tonne BA)	Use industry typical value, 0,015	7,5	Individual facility records	2
B_A: 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	5	Individual facility records	6
A_{shpc}: ash content in packing coke (wt %)	Use industry typical value, 2,5	5	Individual facility records	6
P_{CW} = packing coke weight (tonnes)	Individual facility records	2	Individual facility records	2
E_{FPC} = emission factor of packing coke (t CO_2/t of packing coke)	3,19 [4]	Not relevant	3,19 [4]	Not relevant
O_{FPC} = oxidation	1	Not relevant	1	Not relevant

Parameter	**Tier 1 method**		**Tier 2 method**	
	Data source	**Data uncertainty (± %)**	**Data source**	**Data uncertainty (± %)**
factor of packing coke				

7.6 Calculation of carbon dioxide emissions from the Søderberg process

Carbon dioxide process emissions for Søderberg technologies shall be calculated according to:

$$E_{CO_2} = \left[\begin{array}{c} \left(M_P \times P_C\right) - \left(C_{SM} \times {}^{M_P}\!\!/_{1000}\right) - \left[\left({}^{B_C}\!/_{100}\right) P_C \times M_P \left(\frac{S_p + A_{shp} + H_p}{100}\right)\right]\Bigg] \\ - \left[\left[\left(\frac{100 - B_C}{100}\right) P_C \times M_P \left(\frac{S_c + A_{shc}}{100}\right) - \left(M_P \times C_D\right)\right]\right. \end{array} \right] 3{,}664 \qquad (12)$$

NOTE 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, A_{shp} and C_{SM} from Formula (4). The pitch coking value is a commonly determined parameter for many facilities with Søderberg cells.

where

E_{CO_2}	are the CO_2 emissions in tonnes per year;
M_P	is the total metal production, tonnes aluminium per year;
P_C	is the paste consumption, tonnes per tonne aluminium;
C_{SM}	are the emissions of cyclohexane soluble matter, kg per tonne aluminium;
B_C	is the typical binder content in paste, wt %;
S_p	is the sulphur content in pitch, wt %;
A_{shp}	is the ash content in pitch, wt %;
H_p	is the hydrogen content in pitch, wt %;
S_c	is the sulphur content in calcined coke, wt %;
A_{shc}	is the ash content in calcined coke, wt %;
C_D	is the carbon in skimmed dust from Søderberg cells, tonnes carbon per tonne aluminium;
3,664	is the CO_2 molecular mass: carbon atomic mass ratio, dimensionless.

Parameters used in Formula (12) are defined in Table 4 together with industry typical values for calculating CO_2 emissions for Søderberg technologies.

Table 4 — Typical uncertainty for individual parameters and analyses used in Tier 1 or Tier 2 method for carbon dioxide emissions from Søderberg cells

Parameter[a]	**Tier 1 Method**		**Tier 2 Method**	
	Data source	**Data uncertainty (± %)**	**Data source**	**Data uncertainty (± %)**
M_P: total aluminium production (tonnes per year)	Individual facility records	2	Individual facility records	2
P_C: paste consumption (tonnes per tonne aluminium)	Individual facility records	2-5	Individual facility records	2-5
C_{SM}: emissions of cyclohexane soluble matter (kg per tonne aluminium)	Use industry typical value, HSS – 4,0 VSS – 0,5	30	Individual facility records	15
B_C: typical 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
A_{shp}: 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	20	Individual facility records	10
S_c: sulphur content in calcined coke (wt %)	Use industry typical value, 1,9	20	Individual facility records	10
A_{shc}: ash content in calcined coke (wt %)	Use industry typical value, 0,2	20	Individual facility records	10
C_D: carbon dust from anode (tonnes per tonne aluminium)	Use industry typical value, 0,01	99	Individual facility records	30

[a] The influence of some parameters with high uncertainty is very low on the total GHG emissions.

Referring to Formula (12), the overall uncertainty is approximately 5 %.

8 Methods for calculation of PFC emissions

8.1 Introduction

Three sequential steps described below shall be used to calculate the carbon dioxide equivalent emissions represented by PFC emissions from primary aluminium production.

— Emissions of each of the two PFC gases are first calculated per tonne of primary aluminium produced.

— These emission rates per tonne of aluminium are multiplied by the total production of aluminium during the time period for which the inventory is being developed.

— The equivalent CO_2 emissions are calculated by multiplying the PFC emissions by appropriate Global Warming Potential (G_{WP}) factors.

Two separate approaches are described below for calculating PFC emissions per tonne of aluminium with relative uncertainty varying from low to high.

Tier 1 is a method using a combination of plant specific process data and technology specific slope factor.

Tier 2 is a method using plant specific process data and plant specific slope factor.

Plant specific process data and plant specific slope factors should be measured by using the Tier 2 method with an uncertainty of less than 15 %. Tier 1 is only suitable for the calculation of PFC emissions in case Tier 2 is not feasible for economic or technical reasons.

8.2 Tier 1 method for calculating PFC emissions

This method is based on calculations using site specific anode effect or overvoltage process data but industry average coefficients in place of coefficients calculated from site specific measurements of PFC gases. PFC emission rates and CO_2 equivalent emissions should be calculated as in the Tier 2 method using Formulae (17) and (18) in 8.4.2. The current recommended average slope and overvoltage coefficients are listed in Table 5.

Table 5 — Technology specific slope and overvoltage coefficients for the calculation of PFC emissions per tonne aluminium from AE process data

Technology [a]	**Slope coefficient** [b, c] **[(kg $_{PFC}$/t$_{Al}$) / (AE-mins/cell-day)]**		**Overvoltage coefficient** [b, c, d, e] **[(kg $_{CF4}$/t$_{Al}$) / (mV)]**		**Weight fraction C_2F_6/CF_4**	
	S_{CF_4}	**Uncertainty (±%)**	**O_{VC}**	**Uncertainty (±%)**	$F_{C_2F_6/CF_4}$	**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.

[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 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.

[e] Overvoltage coefficients are not relevant (NR) to VSS and HSS technologies.

The latest revision of the EPA/IAI GHG Protocol should be considered and thereof updated values applied.

The uncertainties indicated in Table 5 refer to the determination of the industry average of the technology-specific coefficients. The plant-specific uncertainties of the PFC calculation using the Tier 1 approach, applying these coefficients, can be significantly higher than those reached through the Tier 2 approach. Data regarding the variation of these values are found in [8].

8.3 Tier 2 method for calculating PFC emissions

This method is based on calculations using site specific anode effect process data, aluminium production data and coefficients based on direct local facility measurements of PFCs. The measurements on which the coefficients are based on should be made according to [11].

8.4 Calculation of PFC emissions from aluminium reduction processes

8.4.1 Step 1 – Calculate the emissions of each PFC gas per tonne of aluminium

8.4.1.1 General

PFC emissions per tonne aluminium shall be calculated by either the slope method or the overvoltage method depending on the type of anode effect process data recorded at the facility.

8.4.1.2 Calculation of emission rate of CF_4 and C_2F_6 per tonne aluminium using anode effect minutes per cell day (Slope method)

The slope coefficient is the kg of CF_4 per metric tonne of aluminium produced, divided by anode effect minutes per cell-day. Since PFC emissions are measured per tonne of aluminium produced, the slope coefficient includes the effects of pot amperage and current efficiency, the two main factors determining the amount of aluminium produced in the pot.

Formulae (13) and (14) shall be used when anode effect minutes per cell day is the anode effect process data correlated with emission rate. The equations shall be applied for each operating potline in the facility to obtain the specific emissions per tonne aluminium produced for each potline.

$$R_{CF_4} = A_{EM} \times S_{CF_4} \tag{13}$$

$$R_{C_2F_6} = R_{CF_4} \times F_{\frac{C_2F_6}{CF_4}} \tag{14}$$

where

R_{CF_4} is the emission rate for CF_4 kg, CF_4 tonne aluminium;

A_{EM} are the anode effects minutes per cell day (= frequency x average duration);

S_{CF_4} is the slope coefficient for CF_4, kg CF_4 per tonne aluminium per anode effect minute per cell day;

$R_{C_2F_6}$ is the emission rate for C_2F_6, kg C_2F_6 per tonne aluminium;

$F_{\frac{C_2F_6}{CF_4}}$ is the weight fraction of $\frac{C_2F_6}{CF_4}$.

8.4.1.3 Calculation of emission rate of CF_4 and C_2F_6 per tonne aluminium using anode effect overvoltage (Overvoltage method)

Some process control systems characterize anode effects by calculating an anode effect overvoltage (A_{EO}) statistic. A_{EO} is defined as the extra cell voltage above the target operating voltage. This shall be 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.

Formulae (15) and (16) shall be used when anode effect overvoltage is the process data correlated with the emission rate. As with the slope method noted above the following equations shall be applied for each individual potline operating at the facility:

$$R_{CF_4} = O_{VC} \times \frac{A_{EO}}{C_E} \tag{15}$$

$$R_{C_2F_6} = R_{CF_4} \times F_{\frac{C_2F_6}{CF_4}} \tag{16}$$

where

R_{CF_4} is the mission rate for CF_4, kg CF_4 per tonne of aluminium;

O_{VC} is the Overvoltage coefficient for CF_4 as calculated from facility specific measurements according to guidance in the *PFC Measurement Protocol* [5];

A_{EO} is the anode effect overvoltage, millivolts;

C_E is the current efficiency for aluminium production, %;

$R_{C_2F_6}$ is the emission rate for C_2F_6, kg C_2F_6 per tonne aluminium;

$F_{\frac{C_2F_6}{CF_4}}$ is the weight fraction of $\frac{C_2F_6}{CF_4}$.

8.4.2 Step 2 – Calculate the total kilogram emissions of each PFC gas

Total PFC emissions shall be calculated from Formulae (17) and (18). For each operating potline, the emission rate (from Step 1) of each PFC gas per tonne of primary aluminium produced shall be multiplied by the tonnes of aluminium produced on that potline to calculate total PFC emissions for the line. Total PFC emissions are calculated by summing the emissions overall operating potlines at the facility [7].

$$E_{CF_4} = R_{CF_4} \times M_P \tag{17}$$

$$E_{C_2F_6} = R_{C_2F_6} \times M_P \tag{18}$$

where

E_{CF_4} are the emissions of tetrafluoromethane, kg CF_4 per year;

$E_{C_2F_6}$ are the emissions of hexafluoroethane, kg C_2F_6 per year;

R_{CF_4} are the emission rates of CF_4, kg per tonne of aluminium produced;

$R_{C_2F_6}$ are the emission rates of C_2F_6, kg per tonne of aluminium produced;

M_P is the metal production, tonnes aluminium per year.

8.4.3 Step 3 – Calculate the total tonnes of carbon dioxide emissions equivalent to the PFC emissions

The CO_2 equivalent emissions for PFC emissions shall be calculated by summing the product of each PFC emission and its respective Global Warming Potential (G_{WP}). The G_{WP} used for this calculation are those noted in [7].

$$E_{CO2-eq} = \frac{\left(G_{WP_{CF_4}} \times E_{CF_4}\right) + \left(G_{WP_{C_2F_6}} \times E_{C_2F_6}\right)}{1000} \tag{19}$$

where

$E_{CO2\text{-}eq}$ is the carbon dioxide equivalent emissions in tonnes per year;

E_{CF_4} are the missions of tetrafluoromethane, kg CF_4 per year;

$E_{C_2F_6}$ are the emissions of hexafluoroethane, kg C_2F_6 per year;

G_{WP} is the Global Warming Potential. Use latest G_{WP} data from IPCC.

8.5 Verification of GHG calculation

8.5.1 Validation of CO_2 emission calculation

The measurements were performed by using a mobile FTIR-system. After checking the homogeneity of the sampling plane (see EN 15259) a heated probe was installed and all relevant components were analysed by the heated FTIR-system (CO_2, CO and moisture). Only oxygen was analysed by means of a paramagnetic measuring system in the exhaust of the FTIR-system. For the measurement of the mass flow the volume flow was measured continuously according to EN ISO 16911 [2, 3]. Measurements were performed for one month at each sampling site. Quality assurance was done prior to the measurements (i.e. linearity) and during the measurements (check gas, zero gas).

8.5.2 Validation of PFC emission calculation

An analysis of the data from PFC measurements at thirty-eight primary aluminium production facilities made after publication of the 2006 updated tier 1 equation coefficients confirms and validates the IPCC Tier 1 methodology for calculation of anode effect related CF_4 and C_2F_6 emissions from primary aluminium production based on plant anode effect process data. The data analysed covered all the major primary aluminium technology types including point feed prebake, side work prebake, vertical stud Søderberg and horizontal stud Søderberg cell types. The analysis of the measurement data also confirmed that the IPCC Tier 1 equation slope and overvoltage parameters for calculation of PFC emission factors from plant anode effect process data conforms to statistical expectations. For the most widely used PFPB technology the expanded measurement data set confirms the accuracy of the 2006 IPCC Tier 1 equation parameter is better than +/-6 %. Similarly, the post 2006 measurement data confirm the documented Tier 1 factors for the other technology types used to produce primary aluminium.

9 Key performance indicators

For calculation of key performance, indicator values obtained from tier 2 methods shall be used, except the case of PFCs for which the values obtained from tier 1 methods based on technology specific factors have a better accuracy.

Methods to be used to compare similar plants:

- total direct emissions from electrolysis (DEE), expressed as tCO_{2eq}/t of aluminium: DEE = sum of CO_2 emissions from anode consumption + PFC emissions expressed as CO_2 equivalent/t electrolysis metal;
- total direct emissions from anode baking, expressed as tCO_{2eq}/t of anode: DAE = sum of CO_2 emissions from process + fuel emissions/t baked anodes;
- total indirect emissions from electrolysis, expressed as tCO_{2eq}/t of aluminium: TIE = electrolysis electricity consumption (MWh/t) * grid specific CO_2-factor (tCO_2/MWh).

It is generally of interest to know how the electricity is generated, i.e. hydro power, gas, coal, nuclear, combination. The GHG emission of hydropower is far lower than e.g. gas generated electricity.

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