Coalition On
Materials Emissions
Transparency

GHG Accounting Methods in the Aluminum Industry

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COMET accelerates supply chain decarbonization by enabling producers, consumer-facing companies, investors, and policymakers to better account for greenhouse gas (GHG) emissions throughout materials supply chains, in harmony with existing GHG accounting and disclosure methods and platforms.

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Executive Summary

Primary aluminum production is one of the world's most GHG-intensive industries, and also one where GHG accounting methods have become the most fully developed. GHG reporting for the primary aluminum sector has largely consolidated under the International Aluminium Institute's (IAI) guidance, although Environment Canada (EC) guidance remains active and Chinese aluminum smelters will soon additionally be required to report their emissions under the China National Development and Reform Commission's (China NDRC) guidelines, meant to support the development of the Chinese emissions trading system. The IAI method largely follows best GHG accounting practices, but aspects of it can be improved, and differences compared to other methods highlight open areas of contention. The most critical points identified are the following:

- **System Boundaries:** Reporting requirements differ substantially between the three methods examined, and are the primary driver of different emissions reporting outcomes as measured in the included case study. EC, designed to contribute to a national GHG inventory, adopts a flexible boundary which only covers processes taking place onsite. China NDRC uses activity data on fuels consumed to measure emissions from combustion without providing adequate clarity on which combustion processes must be included. IAI provides a cradle-to-gate emissions boundary in its most recent Good Practice Guidance for Calculation of Primary Aluminum and Precursor Product Carbon Footprints. In practice, however, many producers reporting emissions through the London Metals Exchange continue to use an older version of IAI guidance that allows users to choose between three levels of system boundary disclosure. No phase-out plan for this older guidance has yet been published. China NDRC and EC provide no details on how cast-house emissions should be included, while IAI does not adequately specify which casting and recasting operations need to be included. All three methods also fail to provide guidance for emissions from processes tied to semi-fabrication such as extrusion and rolling, which often take place within the scrap remelting and refining facilities of primary aluminum producers. These differences need to be reconciled to yield fully comparable and standardized data, and to simplify the accounting process for recyclers.
- **Upstream and Fugitive Emissions:** Upstream emissions sources are not included by EC, and China NDRC only includes emissions from upstream energy production. IAI provides a partial list of emissions factors for upstream inputs in its Scope 3 Calculation Tool, but does not describe how these factors are obtained. All three methods also lack specific guidance for tracking and reporting fugitive emissions, upstream or direct.
- **Emissions Credits:** Accounting methods in the aluminum sector largely exclude the possibility of assigning emissions credits for byproducts with potential uses in other sectors. This avoids the possibility of double counting emissions credits when those other sectors are involved. While the suitability of the waste products and other outputs produced by each metals sector for reuse in other sectors may differ, and legal barriers prevent the reuse of aluminum waste products such as red mud, the approach to credits within the metals sector as a whole should be reconciled to determine how it can be harmonized in a way that best incentivizes decarbonization across the entire sector.
- **Perfluorocarbon (PFC) Emissions:** Updated Intergovernmental Panel on Climate Change (IPCC) guidance means that guidelines provided by EC and China NDRC on how to estimate PFC emissions from electrolysis are now inconsistent with the latest international recommendations. These guidelines should be updated, and regional and national regulations on measuring PFC emissions should also be updated to reflect these changes.
- **Treatment of Scrap:** China NDRC and EC do not touch on incorporation of scrap into final products, even though scrap usage forms an important part of the pathway to reducing emissions in the aluminum sector. IAI imposes transparency requirements on inclusion of pre-consumer and post-consumer scrap, but does not recommend a method for calculating and allocating emissions associated with this scrap because the aluminum industry itself has not reached consensus on the most appropriate method. IAI has shared and documented a number of potential equations for scrap allocation (derived from ISO standards) available in a draft document for public review, but has not yet provided a definitive equation to clarify how users should assign emissions from primary aluminum production, pre-consumer scrap, and post-consumer scrap when calculating a final product carbon footprint.

Acronyms

ASI	Aluminium Stewardship Initiative
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
EC	Environment Canada
ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse Gas
HFC	Hydrofluorocarbon
HSS	Horizontal Stud Söderberg
HVAE	High Voltage Anode Effect
IAI	International Aluminium Association
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
LME	London Metals Exchange
LVAE	Low Voltage Anode Effect
NDRC	National Development and Reform Commission (China)
PCF	Product Carbon Footprint
PFC	Perfluorocarbon
PFPB	Point-Feed Prebake
REC	Renewable Energy Certificate
T&D	Transmission and Distribution
VAP	Value-Added Product

1 Introduction

From its discovery in 1825 to the late 19th century, metallic aluminum was one of the world's rarest and most precious commodities. At a price per ounce nearly double that of gold in the 1850s, the lightweight, conductive and noncorroding metal was seen as "the silver from clay." The capstone of the Washington Monument, famously cast out of aluminum in 1884, is a nod to the metal's value and useful chemical properties. At just 23 centimeters tall and 2.83 kilograms, the capstone was the largest piece of aluminum in the world at the time. Just a few years later, though, the 1886 Hall-Héroult process and the 1889 Bayer process made aluminum available to the masses. The International Aluminium Association (IAI) estimated global production of aluminum in 2020 at over 65 million tons, exceeding all other non-ferrous metals combined. In total, aluminum production is responsible for 2% of global GHG emissions, or 1.1 gigatons of CO2-equivalent (CO2e) emissions annually.[1]

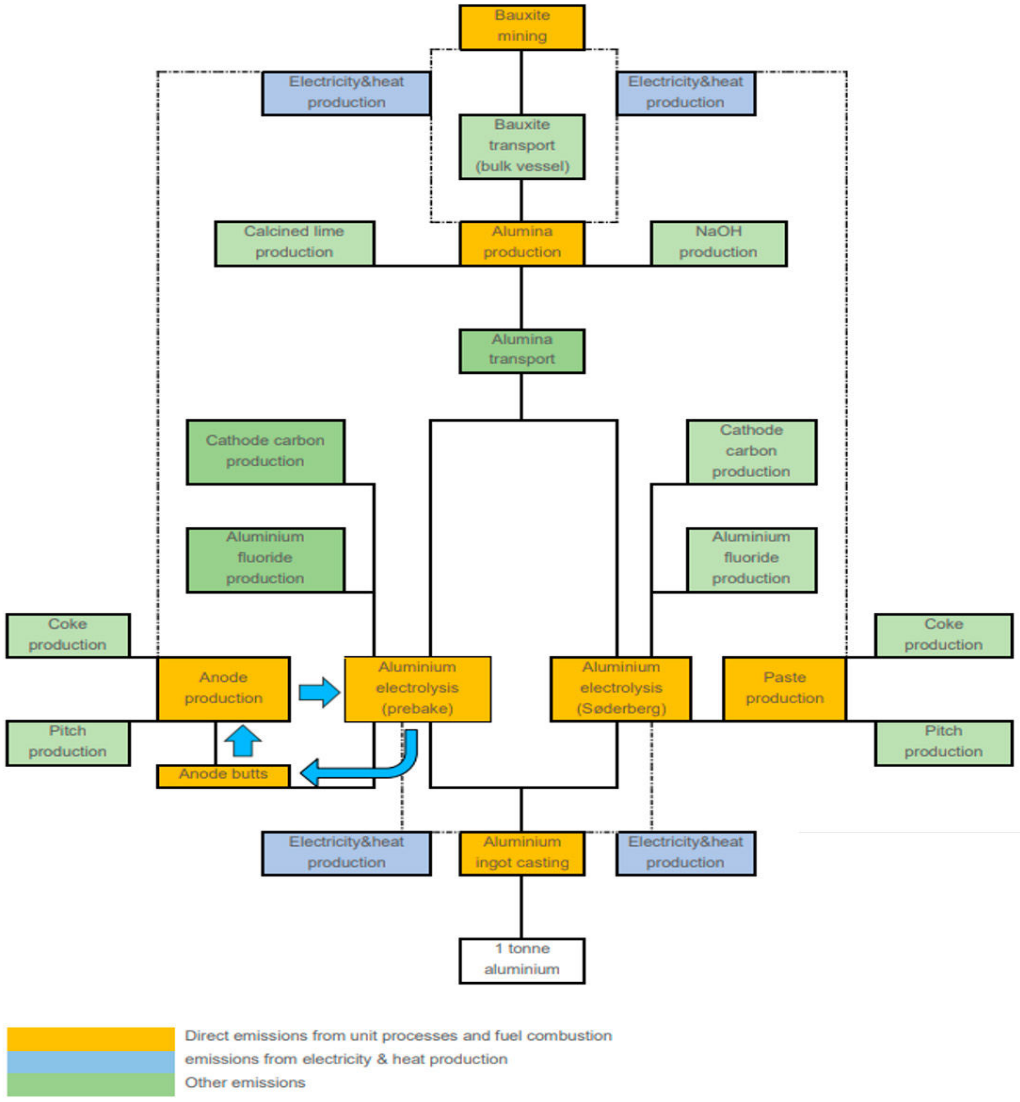

Figure 1. Emissions Sources in Aluminum Manufacturing.[2]

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[1] "Decarbonizing Aluminum: Rolling Out a More Sustainable Sector," Center for Strategic and International Studies, William Alan Reinsch and Emily Benson, February 25, 2022, https://www.csis.org/analysis/decarbonizing-aluminum-rolling-out-more-sustainable-sector.

[2] International Aluminium Institute, "Aluminium Carbon Footprint Technical Support Document," February 15, 2018, 15.

Aluminum production is a high-energy and greenhouse gas (GHG)-intensive process whose weight and importance makes its associated emissions especially important to accurately define and report. At the same time, its complexity presents substantial challenges to accounting. Both stationary and mobile combustion release GHGs including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) into the atmosphere over multiple stages of the industrial process. Smelting requires high quantities of electricity, and while some smelters are situated to take advantage of large-scale green energy sources, others meet their electricity demand by producing and consuming large amounts of fossil energy. Consumption of anodes within the Hall-Héroult electrolytic process, which dominates contemporary primary aluminum production, also releases CO_2, and anode effects cause the release of additional potent GHGs, such as carbon tetrafluoride (CF_4) and hexafluoroethane (C_2F_6). Additionally, sulfur hexafluoride (SF_6) can be vented when used as a cover gas or for electrical insulation. The multiple interconnected systems, substantial electricity consumption, and unique sources of process emissions mean that a robust and comprehensive GHG accounting methodology for primary aluminum producers must strictly define system boundaries and provide satisfactory techniques for either estimating GHG emissions from identified sources or measuring them directly.

1.1 Carbon Accounting Methods Examined

This study compares three complete accounting methodologies for the primary aluminum sector. In addition, this study examines Intergovernmental Panel on Climate Change (IPCC) guidelines on accounting for primary aluminum production for national inventories and regulations associated with the European Union Emissions Trading System (EU ETS).

- **China National Development and Reform Commission, "Guidelines for Accounting and Reporting Greenhouse Gas Emissions: China Electrolytic Aluminum Production Enterprises"** This method was developed to support the goal of developing a carbon emissions trading market outlined in the Chinese government's 12th five-year plan, covering the period from 2011-2015. The China NDRC framework was intended to aid in the development of emissions reporting systems at the local, national, and enterprise levels, to provide a scientific basis for emissions calculations, and to provide an impetus for the development of GHG emissions control plans. Aluminum will be one of the newest additions to a broader emissions trading system (ETS) founded in 2017 for Chinese industries.[3] Initially covering only emissions from coal and natural gas power plants, China's ETS was anticipated to formally incorporate emissions from electrolytic aluminum by the end of 2022, but disputes over data collection have postponed this until 2023.[4] Coupled with additional planning work around including emissions from iron and steel, chemicals, papermaking, and domestic air travel, these changes would increase the size of China's carbon market, already the world's largest, by a further 70%.[5]
- **Environment Canada Greenhouse Gas Division, "Aluminium Production: Guidance Manual for Estimating Greenhouse Gas Emissions"** Environment Canada (EC)'s GHG accounting methodology for primary aluminum production forms part of a suite of similar guidance manuals covering other material and manufacturing sectors developed under the Government of Canada Action Plan 2000 on Climate Change, and is intended for use by facilities operating under Canada's broader regulatory framework to contribute to a national emissions inventory. This specific series of manuals offers a resource for calculation and voluntary reporting of onsite emissions from electrolytic aluminum production, with a scope that deliberately excludes certain indirect emissions sources and segments of the aluminum value chain to avoid implicit or explicit double counting of emissions from overlap with other Canadian guidance documents. While it claims compatibility with the International Aluminium Institute's (IAI) 2003 GHG Emissions Monitoring and Reporting Guidelines, the methodology itself has not been updated alongside more recent revisions to the IAI method.
- **International Aluminium Institute, "Good Practice Guidance for Calculation of Primary Aluminium and Precursor Product Carbon Footprints"** IAI provides the most prevalent guidance on accounting

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[3] Caixin Global, "China's National Carbon Trading Market to Include Cement, Aluminum Next Year, Expert Predicts," June 28, 2021, https://www.caixinglobal.com/2021-06-28/chinas-national-carbon-trading-market-to-include-cement-aluminum-next-year-expert-predicts-101732910.html.

[4] Jim Pollard, "China Carbon Market Expansion Delayed – Caijing," Asia Financial, May 20, 2022, https://www.asiafinancial.com/china-carbon-market-expansion-delayed-caijing.

[5] Chris Busch, "China's Emissions Trading System Will Be The World's Biggest Climate Policy. Here's What Comes Next," Forbes Magazine, April 18, 2022, https://www.forbes.com/sites/energyinnovation/2022/04/18/chinas-emissions-trading-system-will-be-the-worlds-biggest-climate-policy-heres-what-comes-next/.

for product GHG footprints in the sector. The product-level guidance contained in this document, referred to here as the Good Practice Guidance on Carbon Footprints, provides a set of cradle-to-gate guidelines which applies not just to aluminum producers, but throughout the primary aluminum supply chain. However, the Good Practice Guidance on Carbon Footprints does not provide adequate coverage of parts of the supply chain relevant to recyclers, semi-fabricators, and other manufacturers who often engage directly with primary producers. In addition to the Good Practice Guidance on Carbon Footprints, IAI provides supporting documents on which this analysis relies:

- **Aluminium Carbon Footprint Technical Support Document:** This document provides additional technical guidance and details related to calculating emissions from primary aluminum products following LCA principles. The Technical Support Document additionally defines three levels of system boundary disclosure which plants can use in an effort to combine the benefits of rigid system boundaries with the flexibility of reporting requirements some plants may desire. These are referred to in this document as IAI 1, IAI 2, and IAI 3, and the respective differences between them are illustrated in Figure 2. The IAI Good Practice Guidance for Carbon Footprints, which has phased out these disclosure levels for a cradle-to-gate emissions reporting approach to be applied to all producers, serves as an update to this document. However, the Technical Support Document remains available for producers unable to meet all the requirements of the Good Practice Guidance, and various users on the London Metals Exchange continue to use the Technical Support Document to report their emissions footprints. No plan for phasing out this deprecated guidance has yet been published.
- **Good Practice Guidance: Measuring Perfluorocarbons:** This document, referred to here as the PFC Good Practice Guidance, expands on the Technical Support Document to provide more precise guidance on measuring perfluorocarbon (PFC) emissions in light of the updated Intergovernmental Panel on Climate Change (IPCC) sectoral guidelines issued in 2019. The new guidance discards once widely used estimation approaches in favor of recommending several approaches to conducting direct measurement of PFC emissions.
- **Guidelines on Transparency – Aluminium Scrap:** This document describes IAI's requirements for calculating and reporting carbon footprints of aluminum products when scrap or recycled material are incorporated, along with a series of default values for post-consumer scrap shares for users lacking access to primary data.
- **Reference Document on How to Treat Scrap Flows in Carbon Footprint Calculations for Aluminium Products:** Neither the Guidelines on Transparency nor the Good Practice Guidance for Calculation of Primary Aluminum and Precursor Carbon Footprints include specific equations for calculating the final carbon footprints of aluminum products containing scrap because multiple potential methods exist for doing so, the ISO guidelines underlying these methods are in conflict,[6] and the aluminum industry itself has not reached consensus on the most appropriate method. This internal reference document, made available for public comment as of January 2023, identifies the relevant conflicts in these standards pertaining to treatment of emissions from scrap and describes various methods in use for calculating these product carbon footprints (PCFs) with a particular emphasis on sales of pre-consumer scrap from one entity to another.
- **The Aluminium Sector Greenhouse Gas Protocol:** This document specifies how IAI's aluminum sector-specific guidance is to be used within the context off the broader GHG Protocol Corporate Standard. The IAI contribution to the Corporate Standard exists in parallel to its own, more recently developed product guidance.
- **Scope 3 Calculation Tool Guidance:** This document provides guidance on calculating

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[6] The ISO guidelines examined by IAI include ISO 14044:2006 (Environmental management – Life cycle assessment – Requirements and guidelines), ISO 14067:2018 (Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification), ISO 21930:2018 (Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services). They also review the European standard EN 15804+A2:2019 (Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products).

Scope 3 emissions in compliance with the GHG Protocol in accordance with the GHG Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard. As a corporate emissions tool, it is distinct from the product-level value chain guidance contained in the IAI Good Practice Guidance on Carbon Footprints.

- **Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories:** The IPCC produced an initial set of guidelines for building national GHG inventories in 2006, followed by a refinement of the earlier guidelines in 2019. For aluminum, the 2019 refinement included tighter specifications for calculating PFC emissions from high voltage and low voltage anode effects and from cell start-up. Since the IPCC guidelines are intended for national inventories and to cover all sources of emissions within an economy, no system boundaries for aluminum production are included. The language most relevant to the aluminum sector can be found in Volume 3 (Industrial Processes and Product Use, or IPPU), Chapter 4, “Metal Industry Emissions” and Volume 2 (Energy), Chapter 2, “Stationary Combustion.”
- **European Union Emissions Trading System (EU ETS) Monitoring and Reporting Regulation (MRR):** The EU ETS MRR provides rules on how GHG activity should be monitored for sectors whose emissions are subject to regulation under EU ETS. Emissions within EU ETS are capped according to a benchmark system, in which “free allowances” are distributed according to the quantities produced of specified goods and the average GHG emissions of the top-performing 10% of facilities producing each of those goods. For the period 2021-25, free allowances for 1.288 tCO2e/t aluminum are permitted under EU ETS.[7]
  - ◊ **European Standard EN 19694-4:** This regulatory standard, adopted by the German government, provides additional guidance on best practices for measuring emissions from primary aluminum production to support the EU ETS system.

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[7] European Union, “Regulation determining revised benchmark values for free allocation of emission allowances for the period from 2021 to 2025 pursuant to Article 10a(2) of Directive 2003/87/EC of the European Parliament and of the Council,” 2021/447.

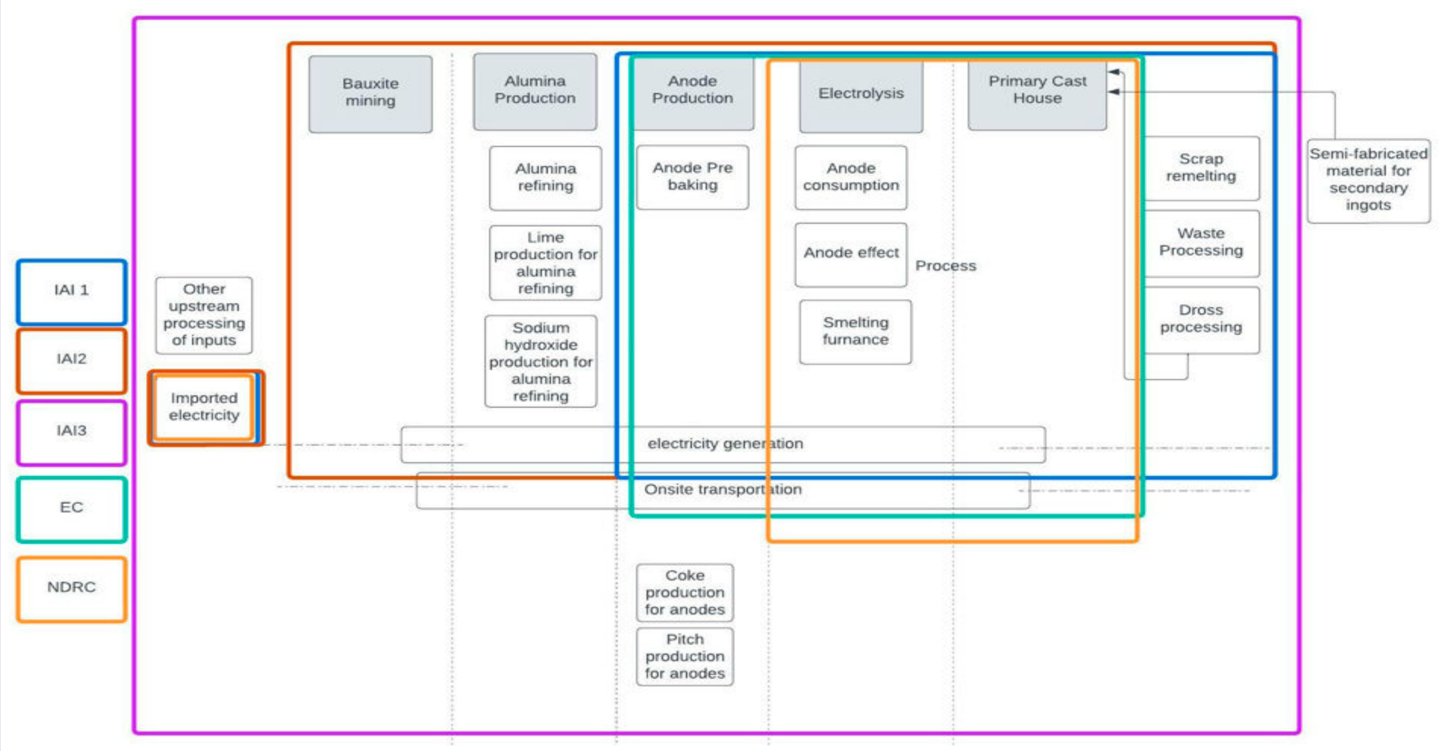

Figure 2. Comparison of System Boundaries

Source: Prepared by the authors based on the listed guidelines.

2 System Boundaries

2.1 Mining of Bauxite and Other Ores

Aluminum starts from the mining of aluminous ores, primarily bauxite. Bauxite is not one single mineral but a mix of the minerals gibbsite ($Al(OH)_3$), boehmite, and diaspore (both AlO(OH)), along with ferrous ores and other trace substances. Bauxite is normally removed from an open-cut mine, then crushed and delivered to an alumina plant for further processing.

Bauxite mining primarily contributes to GHG emissions through stationary and mobile combustion. Only IAI 2, 3, and the IAI Good Practice Guidance on Carbon Footprints specifically direct practitioners to calculate emissions from bauxite mining and transportation. This is to be done using the stationary and mobile combustion workbooks from the GHG Protocol. Emissions from coal, diesel, heavy oil, natural gas, and electricity consumption are to be calculated.

2.2 Alumina Production

Alumina (aluminum oxide, or Al_2O_3), the immediate precursor to primary aluminum production, is produced through the Bayer process. Bauxite is mixed with caustic soda within a digester under conditions of elevated heat and pressure, producing a slurry of sodium aluminate and metal oxides (red mud) that are separated as a waste product with the aid of lime. The sodium aluminate solution is cooled and seeded with alumina to produce hydrated alumina in crystalline form. It is washed, then reduced to pure alumina through calcination in a rotary kiln. Thanks to its high hardness and melting point, alumina is also frequently used outside of the primary aluminum process in major industrial applications ranging from abrasives to glass and ceramics.[8]

Alumina may be produced at primary aluminum facilities or imported from offsite, as may the carbon-intensive inputs, caustic soda, and calcined lime required in the process. IAI 2, 3, and the IAI Good Practice Guidance on Carbon Footprints treat alumina production in the greatest detail, specifying the inclusion of both sub-unit processes within their reporting boundaries. Stationary heat-generating equipment such as digesters, calciners, and dryers are responsible for the vast majority of direct emissions from alumina production, and IAI estimates that less than 1% of total emissions emerge from other processes such as flue desulfurization, combustion of organic compounds in ores, and acid cleaning of equipment. Accordingly, IAI follows 2019 IPCC guidelines in declaring these emission sources immaterial.[9] In contrast with IAI, EC does not specify that emissions from alumina production should be included, although it does require inclusion of the "stationary combustion activities for the purpose of generating heat or work"[10] that form the backbone of the process. EC allows for process-related CO_2 emissions from lime calcination under separate guidance, but does not specify whether any emissions from lime production should be included in primary aluminum reporting. China NDRC includes limestone calcination within its industrial production process emissions, and applies separate calculations for stationary combustion as described in a later section, but does not specify whether alumina production should lie within the reporting boundary. Therefore, reporting requirements for both EC and China NDRC regarding alumina production remain unclear.

2.3 Anode and Cathode Production

Through the Hall-Héroult process, aluminum is smelted from alumina in an electrolytic cell filled with the molten salts aluminum fluoride (AlF_3) and cryolite (Na_3AlF_6). Electricity is conducted from a graphite cathode via the molten solution into a carbon anode. The electrical current induces the oxygen in the alumina to bond with the carbon in the anode, leaving purified aluminum metal to sink to the bottom of the cell as CO_2 is released. Two types of anodes are generally used. The most common, prebaked anodes, are generally prepared from packing coke and coal tar pitch. CO_2 emissions arise from fuel combustion for heat generation as well as off-gassing of volatiles from the mix itself. The less common class of carbon anodes, Söderberg anodes, require no advance preparation and carry a lower upstream emissions footprint than prebake anodes, as they simply comprise a mixture of petroleum coke, coal tar pitch, and a filler paste that is loaded directly into a steel casing within the electrolytic cell itself. The anode is continuously replenished as the carbon is consumed by adding more of the ingredients directly into the anode casing. However, Söderberg anode-based electrolysis is notable for being somewhat more CO_2-intensive overall and substantially more PFC-intensive

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[8] AZO Materials, "Alumina – The Different Types of Commercially Available Grades," May 3, 2002, https://www.azom.com/article.aspx?ArticleID=1389.

[9] International Aluminium Institute, "Good Practice Guidance for Calculation of Primary Aluminium and Precursor Product Carbon Footprints," 12.

[10] Environment Canada, "Aluminium Production: Guidance Manual for Estimating Greenhouse Gas Emissions," 3.

than prebake electrolysis.[11] Because this type of anode is continuously formed, or baked as it absorbs heat within the smelter, Söderberg anodes are considered to be baked in situ instead of prebaked. Recent technological developments such as inert and non-consumable anodes and wetted drained cathodes have the potential to substantially reduce GHG emissions associated with primary aluminum production both from reduced anode consumption and improved energy efficiency.[12] However, aluminum smelting remains overwhelmingly dominated by the carbon-intensive Hall-Héroult process.[13]

EC and all IAI methods include net emissions from onsite anode baking, but China NDRC does not include any calculations for anode baking. This curious omission is only made stranger because the method specifies that "the dominant technology of the production of electrolytic aluminum in China is PFPB (point-feed prebake), which is among the internationally advanced technologies." PFPB production introduces more significant upstream emissions footprint into Chinese primary aluminum production than Söderberg production would, but China NDRC has for some reason chosen to exclude these emissions from its rules.

For both IAI and EC, emissions from anode baking are generally calculated in a three-step process, with minor differences for certain steps:

1. **Combustion within the anode baking furnace:** Direct emissions are calculated from the consumption of fuels such as coal, diesel, heavy oil, and natural gas. IAI additionally includes emissions from electricity consumption, while EC classifies direct emissions from electricity production as stationary combustion.

2. **Combustion of volatiles released from the anode during baking:** Both IAI and EC apply a mass balance approach to calculate the CO_2 emissions released from within the anode during the baking process. For both, the difference between the initial weight of the "green" unbaked anodes and the sum of the weight of hydrogen in the green anodes, the weight of the baked anodes, and the weight of the waste tar collected are taken and multiplied by 44/12 to translate this mass of carbon into the mass of CO_2 emitted. This calculation is given by the following equation from EC:

$$\text{Emissions}_{CO_2} = \left(\text{GAW} - \text{BAP} - \left(\frac{\%H_p}{100} \text{ x } \frac{\%PC}{100} \text{ x GAW}\right) - \text{RT}\right) \text{ x } \frac{44}{12}$$

Where: GAW = green anode tonnage (tonnes);
BAP = baked anode production (tonnes);
Hp = hydrogen content in pitch (%);
PC = average pitch content (%) in green anode;
RT = recovered tar (tonnes);
44/12 = conversion factor from carbon to CO_2

Compared to EC, IAI uses a slightly simplified equation which multiplies the hydrogen content of the green anodes as a whole by the weight of the green anodes, rather than multiplying the hydrogen content of the pitch by the pitch content of the green anodes and then again by the weight of the green anodes. This implies a possible source of discrepancy if the green anodes are baked with any source of hydrogen other than pitch. IAI users are also required to report the total weight of their green anodes at a minimum, while EC users are provided a default value to calculate the weight of their green anodes if they only have access to the quantity of pitch consumed.

3. **Combustion of packing furnace material:** In addition to the release and combustion of volatile gases, a portion of the packing coke will also combust under the heat of the furnace and generate further GHG emissions. Like combustion of volatiles, the same general mass balance approach is applied by both IAI and EC. Packing coke consumption per ton of baked anode is multiplied by baked anode production in tons to obtain total packing coke consumption, then multiplied by a term representing the content of carbon consumed, and finally, by the 44/12 conversion factor representing CO_2 emissions. This calculation is represented by the following equation from EC:

$$\text{Emissions}_{CO_2} = \left(\text{PCC x BAP x } \frac{100 - \%Ash_{pc} - \%S_{pc} - \%Imp}{100}\right) \text{ x } \frac{44}{12}$$

Where: PCC = packing coke consumption per tonne of baked anode (tonnes coke/tonnes anodes);
BAP = baked anode production (tonnes);
Ashpc = ash content in packing coke (%);
Spc = sulfur content in packing coke (%);
Imp = content of other impurities (%):
44/12 = conversion factor from carbon to CO_2

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[11] "Greenhouse Gas Emissions Intensity – Primary Aluminium," International Aluminium Statistics, November 3, 2022, https://international-aluminium.org/statistics/greenhouse-gas-emissions-intensity-primary-aluminium/

[12] Obaidat, Mazin et al, "Energy and Exergy Analyses of Different Aluminum Reduction Technologies," *Sustainability* 10.4, April 17, 2018, 1216.

[13] Light Metal Age, "Primary Aluminum: Inert Anode and Wettable Cathode Technology in Aluminum Electrolysis," February 19, 2020, https://www.lightmetalage.com/resources/patents/primary-aluminum-inert-anode-and-wettable-cathode-technology-in-aluminum-electrolysis/.

IAI's equation does not include the percentage content of impurities other than ash and sulfur.weight of their green anodes if they only have access to the quantity of pitch consumed.

In general, the calculation methods used by EC and IAI will yield similar or identical results provided the user knows and reports the composition of its packing coke and prebaked anodes. Results will differ, however, if the default values included in each method are applied instead. IAI uses representative industry values,[14] while EC uses separate industry average values provided by IAI but dating back to 2003. These different composition parameters are summarized in Table 1.

EU ETS allows the use of an alternative mass balance equation which takes the difference between the total carbon within green anodes and baked anodes and multiplies it by a conversion factor representing CO_2 emissions tied to the missing carbon. In contrast with the three-step process above, this requires data on these carbon contents in addition to anode weight. Without a reliable way to measure the carbon content of baked anodes, this approach cannot be expected to produce an identical value to the above approach.

Finally, EC includes mass balance calculations similar to those for anode production for onsite emissions from cathode production, specifying that although no default values are available for cathode composition, green cathodes can be expected to have a similar composition to green anodes. IAI 3 and the IAI Good Practice Guidance on Carbon Footprints require inclusion of emissions from cathode production, but IAI does not provide a method for calculating these emissions. Differences in emissions from anode baking calculated under each method are illustrated in the Case Study.

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[14] IAI neither cites a formal source nor provides a clear date for these values.

Table 1. Default Composition Parameters for Anode Prebaking

Parameters	IAI Internal Values	EC (IAI 2003)
Hydrogen in green anode, %[a]	0.5%	N/A
Hydrogen in pitch, %	N/A	4%
Pitch content, %	N/A	15%
Recovered Tar, t/t baked anode	0.005 (Reidheimmer furnace), 0 (All other furnaces)	
Packing coke, t/t baked anode	0.015	0.010
Ash content in packing coke, %	2.5%	5% (coal coke)
		0.2% (petroleum coke)
Sulphur content in packing coke, coal coke, %	2%	3%
Sulfur content in packing coke, petroleum coke, %		3%
Other impurities, %	N/A	0.1%

Source: Prepared by the authors based on the listed guidelines.

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[a] IAI directly provides the hydrogen content of the green anode, while EC separately provides the hydrogen content of the pitch and the pitch content of the anode. EC's figures would yield a hydrogen content of 0.6% for a green anode.

2.4 Electrolysis

During electrolysis in the smelting pot, alumina is dissolved in molten cryolite (Na_3AlF_6) and aluminum fluoride (AlF_3) is added to the solution to reduce the overall melting point. A current is run through the solution from the graphite cathode to the carbon anode. Oxygen from the alumina combines with carbon in the anode, leaving behind aluminum metal to accumulate on the cathode for collection on a regular basis.

2.4.1 Anode Consumption

As oxygen combines with the carbon in the anode, CO_2 emissions are generated in proportion to the carbon in the anode which has been consumed. Calculating these emissions will vary depending on whether prebaked anodes or Söderberg anodes are in use, but other than minor differences in presumed anode composition and consumption rate, few meaningful differences exist between the methods.

Table 2. Default Compositions for Prebaked and Söderberg Anodes

	China NDRC	**EC**	**IAI**
Prebaked Anodes			
Net carbon anode consumption, t/t Al	.42 t	.4 t	.42 t
Sulfur content in anode, %	2%	1.6%	2%
Ash content in anode, %	.4%	.8%	.4%
Fluorine and other impurities content in anode, %	N/A	.4%	N/A
Söderberg Anodes			
Paste consumption, t/t Al	N/A	.51 t	.51 t
Benzene/cyclohexane soluble matter, t/t Al	N/A	4.0 kg (horizontal stud) .5 kg (vertical stud)	.5 kg (vertical stud)
Binder content in paste, %	N/A	25-30%	27%
Sulfur content in pitch, %	N/A	.55%	.6%
Ash content in pitch, %	N/A	.15%	.2%
Hydrogen content in pitch, %	N/A	4%	3.3%
Sulfur content in calcinated coke, %	N/A	1.8%	1.9%
Ash content in calcinated coke, %	N/A	.1%	.2%
Carbon dust from anode, t/t Al	N/A	N/A	.01%

Source: Prepared by the authors based on the listed guidelines.

For prebaked anodes, all three methodologies apply a similar mass balance approach. For IAI and EC, the net mass of carbon anode consumed per ton of aluminum produced is multiplied by a factor which subtracts out the sulfur and ash content, then multiplied again by 44/12 to represent the weight relationship between elemental carbon and carbon dioxide. EC's equation below additionally adjusts for impurities from fluorine and other sources. Unlike the other methods, EC allows the ash and sulfur contents of green anodes to be used. According to EC, the error this introduces into the calculation is believed to be negligible – .01% and .1% for sulfur and ash, respectively. EC, whose equation is illustrated below, also applies slightly different default values for sulfur and ash content than the other two methods. The resulting small decrease in reported emissions from prebake anode consumption under EC is illustrated in the Case Study. Prebake anodes are consumed until there are butts that can no longer be fixed inside the smelter, after which point the anode butts are recycled into newly baked anodes, so all three methods measure net anode consumption to avoid double counting.

$$\boxed{\text{Emissions}_{CO_2} - \text{NCC x MP x } \frac{(100 - \%S_a - \%\text{Ash}_a - \%\text{Imp}_a}{100} \text{ x } \frac{44}{12}}$$

Where: NCC = net carbon consumption per tonne of aluminum;
MP = total aluminum production (tonnes);
Sa = sulfur content in baked anodes (%);
Asha = ash content in baked anodes (%);
Impa = content of fluorine and other impurities in baked anodes (%);
44/12 = conversion factor from carbon to CO_2

Söderberg anodes contain substantially more ingredients, but the general approach is similar. Total paste consumption is modified by a series of factors including emissions of cyclohexane soluble matter, the binder content of the paste, the sulfur content of the paste, the ash content in the pitch, the hydrogen content in the pitch, and the sulfur content of the calcined coke to arrive at the amount of carbon loss associated with the consumption of the anode, which is then multiplied by the conversion factor of 44/12 to arrive at CO_2 emissions. Because Söderberg anodes are continuously consumed, no anode butts are produced, and no calculation of net anode consumption is necessary. IAI's calculation, below, also includes an adjustment for the net amount of carbon dust left behind after anode consumption per ton of aluminum.[15] Until the mid-2000s, China's aluminum production was primarily reliant on Horizontal Stud Söderberg (HSS) technology. However, according to the China Non-Ferrous Metals Industry Association (CNIA), aluminum production in China has entirely switched over to PFPB. Therefore, China NDRC does not include a calculation for emissions from Söderberg anode consumption because the industry reports that it is no longer domestically relevant.[16]

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[15] To simplify communication of differences between equations used by EC and IAI, the more complicated form was included as an equation for each relevant process with omissions in the other methodology described in the text. EC's equation is more complex for prebaked anodes, while IAI's equation is more complex for Söderberg anodes.

[16] Jerry Marks and Chris Bayliss, "Aluminum – Meeting the Challenges of Climate Change," *JOM* 62.8 (August 2010), 33-36, https://www.tms.org/pubs/journals/jom/1008/marks-1008.html.

$$E_{CO_2} = \left[\left(\frac{\text{TPC x PC}}{100}\right) + \left(\frac{\text{Coke x CC}}{100}\right) + \left(\frac{\text{TPCC x PCC}}{100}\right) - \text{TWC} + \left(\frac{\text{PA x PAC}}{100}\right) - \left(\frac{\text{SA x SAC}}{100}\right)\right] \text{x} \frac{44}{12}$$

Where:
ECO_2 = annual CO_2 emissions (tonnes);
MP = total annual aluminum production (tonnes);
PC = paste consumption (tonnes paste / tonnes aluminum);
CSM = emissions of cyclohexane soluble matter (kg matter / tonnes aluminum);
BC = typical binder content in paste (%);
Sp = sulfur content in pitch (%);
Ashp = ash content in pitch (%);
Hp = hydrogen content in pitch (%);
Sc = sulfur content in calcined coke (%);
Ashc = ash content in calcined coke (%);
CD = carbon dust from Soderberg anode (tonnes dust / tonnes aluminum);
44/12 = conversion factor from carbon to CO_2

Unlike anodes, cathodes are not directly consumed during the electrolytic process. However, they absorb aluminum and fluoride over time, degrading until they can no longer function. The resulting "spent potliner" then becomes a form of hazardous waste which must be dealt with.[17] IAI 3 and the IAI Good Practice Guidance on Carbon Footprints are the only methods which require reporting of emissions from disposal of spent potliners, as well as from other forms of waste such as red mud. Finally, aluminum fluoride production creates an upstream carbon footprint which only IAI 3 and the IAI Good Practice Guidance on Carbon Footprints account for.

2.4.2 Alternative Mass Balance Approaches to Anode Production and Consumption

For both anode baking and anode consumption, EU ETS applies a mass balance approach that "considers all carbon in inputs, stocks, products, and other exports from the mixing, forming, baking, and recycling of electrodes as well as from electrode consumption in electrolysis." This alternative method theoretically arrives at the same result by subtracting the mass of carbon in anode butts from the total mass of carbon in baked anodes to arrive at the carbon released as CO_2 over the course of electrolysis.

IAI, under GHG Protocol guidance published in 2006, also includes an alternative method for calculating a CO_2 process emissions inventory from anode mixing, baking, and consumption. Total CO_2 emissions for these processes are calculated by first summing up purchases of pitch, coke, anodes, and packing coke, then multiplying these by the estimated carbon content of each raw material, and finally subtracting the total estimated carbon contained within organic byproducts like sold anodes, ash, and sludge. The missing carbon is then assumed to have been released as CO_2 or oxidized from other gases into CO_2. This alternate method is not included in the most recent Good Practice Guidance on Carbon Footprints.

The alternate equation from the GHG Protocol is provided below:

$$E_{CO_2} = \left[\left(\frac{\text{TPC x PC}}{100}\right) + \left(\frac{\text{Coke x CC}}{100}\right) + \left(\frac{\text{TPCC x PCC}}{100}\right) - \text{TWC} + \left(\frac{\text{PA x PAC}}{100}\right) - \left(\frac{\text{SA x SAC}}{100}\right)\right] \text{x} \frac{44}{12}$$

Where:
E_{CO_2} = tCO_2 emissions
TPC = total pitch consumed
PC = carbon content of pitch, wt %
Coke = total coke consumed, t
CC = carbon content of coke, wt %
TPCC = total packing coke consumed, t
PCC = carbon content of packing coke, wt %
TWC = total carbon byproducts or waste, t
PA = total mass of purchased anodes, t
PAC = carbon content of purchased anodes, wt %
SA = total mass of sold anodes, t
SAC = carbon content of sold anodes, wt %

This method simplifies the standard approach applied by EC, the IAI Good Practice Guidance on Carbon Footprints, and the IAI Technical Support Document by applying a mass balance approach across the entire anode production and consumption cycle. However, it does not provide separate estimates of CO_2 emissions from each individual process, which prevents a process-by process approach to emission reduction. Provided the estimates of carbon content for the raw and prepared materials involved are consistent, each method should be expected to produce similar aggregated results.

2.4.3 Anode Effects and Other Sources of PFC Emissions

Aluminum electrolysis does not always perfectly follow the chemical formula. If the alumina in the electrolyte falls below the concentration required to sustain the reaction, then voltage will rise to exceed the normal range of operation. This overvoltage event, referred to as a High Voltage Anode Effect (HVAE), causes the cryolite to react with the carbon anode and release the potent PFCs CF_4 and C_2F_6. Recent research outlined in the 2019 IPCC

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[17] Pong, T.K. et al, "Spent Potlining – A Hazardous Waste Made Safe," *Process Safety and Environmental Protection* 78.3 (May 2000), 204-208.

revision has identified a second class of anode effects, Low Voltage Anode Effects (LVAE), in which voltage exceeds operation parameters at a localized scale within the anode and at a level which produces only CF_4 emissions. Additionally, PFCs can also be released during Cell Start-Up (CSU) due to rapidly changing and inconsistent levels of voltage within the cell.

Because LVAEs are not as clearly detectable as cell overvoltage events, accounting methods which were developed before research into LVAE emissions do not take them into account. This is particularly the case for methods which have not been updated since the 2019 IPCC refinement, which includes some nine separate methods for estimating PFC emissions from HVAEs, LVAEs, and CSU in addition to guidelines for direct PFC emissions measurement. IAI has since updated its methodology by publishing its PFC Good Practice Guidance based on the updated IPCC guidelines, but EC and China NDRC have not made similar updates.

Under current EC and China NDRC guidance, as well the IAI Technical Support Document from 2018 which continues to be applied by various primary aluminum manufacturers, PFC emissions from anode effects can be estimated using a technique called the slope method. The total duration of anode effects for a smelting pot in a single day, measured using a voltmeter, is multiplied by daily aluminum production for that day and pot-specific coefficients for the rate of CF_4 and C_2F_6 production during anode effects to yield an estimate of the total emissions. Slope coefficients are unique for each smelting pot, but each method provides default figures in case direct measurement is not completed. EC guidance also allows for the use of an alternative method, the Pechiney method, which sums the difference between the cell voltage and the standard operating voltage for each second of an anode event, then divides the cumulative overvoltage by the number of seconds in the reporting period to obtain the average overvoltage. This average overvoltage is then compared with PFC emissions to obtain an overvoltage coefficient. In general, the overvoltage method has fallen out of favor in the aluminum industry, and secondary data on overvoltage coefficients are no longer updated, according to IPCC.[18]

The differences between Table 3's values, differentiated by pot and anode type, highlight how dependent these coefficients are on the local characteristics of the technology used. Far from making a useful contribution to reliable PFC emissions calculations, these values only stress just how unreliable default calculations are for this process when primary data is not in place, particularly using equations predating the 2019 refinement. Because of this dependency on local conditions, EC and IAI do not accept estimates using secondary data for average CF_4 and C_2F_6 emissions per ton of aluminum produced. China NDRC is alone in permitting this Tier 1-style approach, assigning emissions factors of .034 kg CF_4/t Al and .0034

Table 3. Default Slope Coefficients

	China NDRC	**EC**	**IAI (2018)**
CF_4	.143	.14 (center prebaked)	.40
		.29 (side prebaked)	
		.067 (vertical Söderberg)	
		.18 (horizontal Söderberg)	
C_2F_6	.0143	.018 (center prebaked)	.04
		.029 (side prebaked)	
		.003 (vertical Söderberg)	
		.018 (horizontal Söderberg)	

Source: Prepared by the authors based on the listed guidelines.

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[18] Intergovernmental Panel on Climate Change, "Methodological issues for primary aluminium production," *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, 4.43.

kg C_2F_6/t Al according to figures provided by the China Nonferrous Metals Industry Association.

What if an operator decides to measure these emissions more accurately? Practitioners using the IPCC refinement can calculate emissions separately for HVAEs, LVAEs, and CSU on the basis of factors, outlined in a series of decision trees included in Appendix III, that point to either a Tier 1, Tier 2, or Tier 3 method. Tier 1 methods apply emissions factors on the basis of production quantity; Tier 2 methods apply the slope method or the non-linear method, which extrapolates HVAE emissions from the measurement of individual anode effects; and Tier 3 methods either directly measure PFC emissions or estimate them according to localized emissions factors and LVAE/HVAE ratios developed according to good practice guidelines jointly developed by the US EPA and IAI.[19] IAI's PFC Good Practice Guidance singles out direct measurement (Tier 3) as the simplest and most reliable means of PFC emissions reporting since LVAE emissions cannot be reliably associated with underlying existing activity data.[20] IAI's recommended direct PFC measurement options include continuous monitoring via laser, real-time extractive sampling, and sample-based averaging, according to a decision tree which factors in reporting requirements and cost.[21]

The 2019 refinement raises an additional challenge for the PFPB technologies highlighted in the China NDRC method, and a significant opportunity to reduce emissions. While many PFPBs apply "automatic anode effect intervention or termination" to stop HVAEs when they occur by adjusting the alumina feed rate or raising the anodes, some PFPB systems require manual intervention. Higher PFC emissions result when this intervention is not done promptly. Data provided by IAI indicates that PFC emissions from PFPB operations in China in 2019 were an alarming outlier compared to the average for the rest of the world. This could indicate that Chinese PFPB systems are not outfitted with automatic intervention technology that could drastically limit the PFC emissions resulting from these events. This data could also highlight excessive PFC emissions from sources such as LVAEs which would not be captured under the slope methodology applied by China NDRC. Introducing direct measurement along the lines of IAI's recommendations could provide greater clarity on the issue. **World**[22]

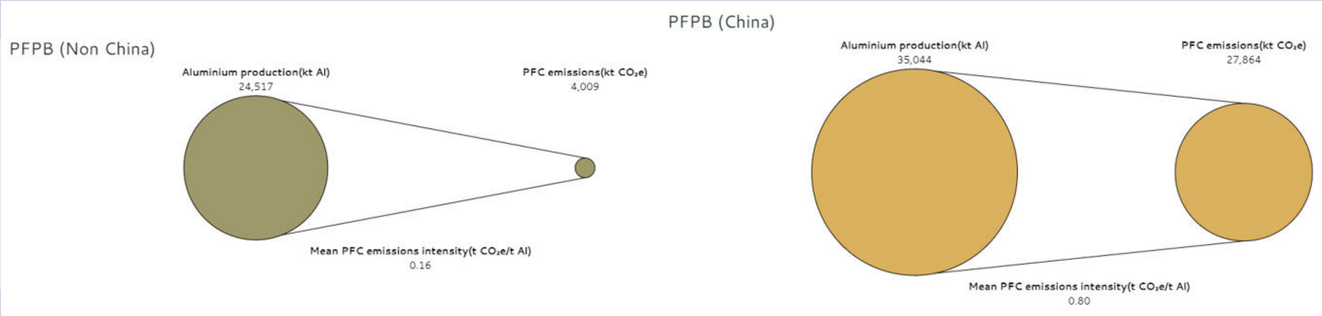

Figure 3. PFC Emissions from PFPB Operations in China vs. the Rest of the World.[22]

Source: International Aluminum Statistics.

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[19] Ibid., 4.44.

[20] International Aluminum Institute, "Good Practice Guidance: Measuring Perfluorocarbons," 3.

[21] Ibid., 7.

[22] International Aluminum Statistics, "Perfluorocarbon Emissions," 2019, https://international-aluminium.org/statistics/perfluorocarbon-pfc-emissions/.

2.5 Cast-house and Scrap Recycling

Once liquid primary aluminum is drained out of the smelting pot, it is delivered to the cast-house. Its first stopping point is a holding furnace in which the molten metal is cooled, with the aid of "run-around scrap" (internal scrap) trimmed from the prior shaping of aluminum ingots, to the casting temperature. Once reached, the metal is sawed into the basic shapes and forms of aluminum ingots which can either undergo semi-fabrication onsite or be delivered to downstream facilities for further shaping and processing. External scrap may also be imported into the cast-house for reshaping into aluminum ingots, but it must first be heated to the casting temperature before it can be reprocessed. As aluminum casting is entirely a heat-based process with no process emissions, only emissions from stationary combustion and electricity are relevant.

Only IAI explicitly describes how to account for emissions from the cast-house. Under IAI's guidance, run-around scrap and imported aluminum metal receive different treatments. Run-around scrap is used to cool the liquid aluminum mixture, and no additional fuel is required to remelt it. On the other hand, fuel must be consumed to remelt purchased aluminum scrap. Fuel can also be used within remelting, refining, or semi-fabrication processes to melt solid ingots when the purchased aluminum is mixed with solid ingots and not liquid aluminum, but IAI does not account for these operations. IAI does not define exactly which casting operations should be included in calculations of product emissions intensity, even though production can involve multiple casting and recasting processes. Of particular concern is the failure to include guidance on emissions from semi-fabrication facilities, which produce inputs for secondary aluminum producers yet are not considered by IAI to form part of the primary aluminum supply chain.

Since aluminum ingots are composed of a mixture of primary aluminum from onsite, purchased pre-consumer and post-consumer scrap, and run-around scrap from onsite, PCFs representing the emissions intensity of the end output of the aluminum operation should be weighted according to its composition and the emissions intensity of each of its input sources. IAI does not include specific instructions for this calculation in its Good Practice Guidance on Carbon Footprints,[23] but under its guidelines for transparency for aluminum scrap, IAI requires producers to explain how carbon footprints are calculated for products containing scrap, especially pre-consumer scrap.[24] Users must at a minimum report an estimated input percentage from post-consumer scrap and from all other scrap types excluding run-around scrap, but including input from aluminum-containing waste products such as dross. IAI also furnishes default values on average post-consumer scrap shares by region for users lacking this specific data.

For IAI and the aluminum industry at large, calculating and assigning emissions for scrap-containing products is a field of active debate. In a reference document which was made available for public comment in January 2023, IAI notes that it cannot provide a single equation for weighting and allocating emissions from the various types of scrap to final products because the industry itself, which it represents, has not reached any form of consensus. IAI goes on to state that conflicts between the ISO and European standards outlining how the environmental impact of scrap should be reported are the sources of these disagreements, before presenting potential calculation and allocation approaches which could meet the needs of these standards. In the interim, IAI's scrap transparency guidelines are intended to provide a data foundation so that all forms of scrap can be properly integrated into PCFs once an approach is agreed upon.

Without providing specific examples of the mass balance calculation producers should be applying, this guidance currently falls short when it comes to providing guardrails for accurate accounting of scrap inputs. Certain industry bodies such as the Aluminium Stewardship Initiative (ASI) provide low-carbon certifications that require reporting the use of scrap,[25] but this lack of clarity complicates efforts to understand whether emissions reductions were achieved through increased usage of scrap or through decarbonization of the main industrial process. Global constraints on the supply of scrap makes clarifying these additional paths to decarbonization especially important; IAI anticipates that recycled aluminum is only anticipated to meet 50% of global demand by 2050.[26]

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[23] International Aluminium Institute, "Good Practice Guidance for Calculation of Primary Aluminium and Precursor Product Carbon Footprints," 20.

[24] International Aluminium Institute, "Guidelines on Transparency – Aluminium Scrap," 1.

[25] "ASI Standards," Aluminium Stewardship Initiative, https://aluminium-stewardship.org/asi-standards/overview.

[26] "Post-consumer aluminium scrap tops 20 million tonnes for the first time," International Aluminium, May 25, 2021, https://international-aluminium.org/post-consumer-aluminium-scrap-tops-20-million-tonnes-for-the-first-time/.

In its reference document on scrap flows, IAI specifically seeks to provide clarity on how emissions should be allocated from process scrap, a form of pre-consumer scrap comprising primary aluminum which is removed during one process step and reused in a later process step, which this scrap crosses the boundary between product systems. This can be visualized as scrap removed during semi-fabrication and sold to a different facility which remelts and integrates it into the aluminum flows for its own products.

Reaching consensus throughout the aluminum industry on an appropriate accounting method for process scrap is challenging in part because the pertinent ISO standards are unclear as to whether this scrap should be considered a waste product, intended for disposal by the original user, or a coproduct intended for use as an input for a separate process. ISO 14044 only dictates that allocation should not result in emissions from the system not being counted or being double-counted. ISO 14067 provides equations for both closed-loop and open-loop allocation of emissions related to recycled material, but without making a distinction between pre-consumer and post-consumer scrap. On the other hand, ISO 21930 specifies that waste generated during production should not be considered a co-product even if it is ultimately transformed into a useable output, and EN 15804+A2 takes the opposite tack by requiring that process scrap be treated as a coproduct.

Because no definitive approach to allocating emissions from process scrap can be drawn from these guidelines, IAI describes three categories of approaches which could be applied to allocating emissions between sellers and purchasers of process scrap:

1. Co-Product Allocation: this method defines the emissions footprint of process scrap according to the GHG intensity of the seller's primary aluminum operation and allocates emissions based on the quantity of process scrap sold, typically on a mass basis;
2. Cut-Off Approach: this method treats process scrap as waste with no emissions footprint. Under the cut-off approach, selling pre-consumer scrap will not reduce a producer's carbon footprint;
3. Substitution Approach: this method assumes that purchased process scrap displaces the purchaser's primary aluminum production and assigns an emissions footprint according to the GHG intensity of the primary aluminum not produced.

Other considerations up for debate by IAI include whether mass allocation or economic allocation should be preferred (mass allocation is generally preferred, but semi-fabrication consumes energy at a rate which is not related to the mass of scrap it generates), whether process scrap is substitutable for primary aluminum as is or whether it must be remelted into ingots before reaching substitutability (in which case emissions from remelting process scrap would also require allocation), and whether the GHG intensity of the purchaser or the average regional GHG intensity should be applied within the substitution approach.

2.6 Stationary Combustion

Stationary combustion refers to the combustion of fuels within fixed facilities. The heat generated from stationary combustion can either be used within an industrial process by itself or to generate electricity or steam, which can then either be consumed onsite or exported offsite. As discussed above, stationary combustion plays a role in many industrial processes within the primary aluminum supply chain. For bauxite mining, onsite stationary combustion is used to power main stationary process equipment. Aluminum hydroxide production uses stationary combustion to provide steam to the digester, while refining these hydrates into alumina requires stationary combustion to heat both kilns for calcination and dryers for the production of specialty alumina for applications outside the aluminum supply chain such as glass and ceramics.[27] Stationary combustion is also involved in anode prebaking, paste production, and heat generation for smelting pots and the cast-house. Finally, auxiliary, emergency, and pollution control equipment at each stage of the supply chain are often powered by stationary combustion processes. This includes equipment used for disposal of waste products. Stationary combustion generates CO_2, N_2O and CH_4 emissions, which are aggregated as CO_2e and reported under each methodology according to 100-year Global Warming Potential (GWP) values provided by IPCC.

Table 4 gives an overview of the stationary combustion emission sources included in each method.

The three disclosure levels in the IAI Technical Support Document incorporate a source-based approach which makes defining a reporting boundary for stationary combustion relatively simple. IAI states outright that disclosure level 1 includes heat for power generation, anode production, and electrolysis; disclosure level 2 adds combustion emissions from bauxite mining and alumina production; and disclosure level 3 incorporates combustion emissions from processing of dross and other waste products. The more current IAI Good Practice Guidance on Carbon Footprints follows the same system boundary for these emissions as IAI 3. However, IAI does not specify any particular calculation method for reporting emissions from waste processing.[28]

China NDRC applies a fuels-based rather than a

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[27] Sleppy, W.C. et al, "Non-Metallurgical Uses of Alumina and Bauxite," *Essential Readings in Light Metals: Alumina and Bauxite*, ed. Don Donaldson, 2013.

[28] International Aluminium Institute, "Good Practice Guidance for Calculation of Primary Aluminium and Precursor Product Carbon Footprints," 32.

Table 4. Stationary Combustion Emission Sources

	Bauxite Mining	Heat for Alumina Production	Heat for Power Generation	Heat for Anode Production	Heat for Electrolysis	Heat for Cast-house	Heat for Dross/Waste Processing
EC	No	Unspecified	Yes	Yes	Yes	Unspecified	Unspecified
IAI 1	No	No	Yes	Yes	Yes	Yes	No
IAI 2	Yes	Yes	Yes	Yes	Yes	Yes	No
IAI 3	Yes	Yes	Yes	Yes	Yes	Yes	Yes
NDRC	No	No	Yes	Unspecified	Yes	Unspecified	Unspecified

Source: Prepared by the authors based on the listed guidelines.

source-based approach to its reporting boundary, which it defines according to operations which take place within "electrolytic aluminum production enterprises."[29] This likely excludes bauxite mining, but it is unclear whether combustion emissions from alumina production are to be included because alumina can either be produced onsite or imported. Process-related emissions are only included for electrolysis, which means it is uncertain whether China NDRC intends combustion emissions from the other core processes of primary aluminum production such as anode production, casting, and waste processing to be included. EC includes "all stationary combustion activities for the purpose of generating heat and work,"[30] but allows users to generate their own system boundary while excluding consideration of any indirect emissions. Inclusion of process emissions calculations for anode production and electrolysis makes it clear that these are to be included, but emissions from alumina production, the cast-house, and waste processing will all cause reported site intensity to vary depending on whether they take place onsite or offsite. Alumina for the facility described in the Case Study is produced offsite as a way of demonstrating how these flexible system boundaries will cause site emissions intensity to vary between the methods.

Default emissions factors used to calculate emissions from fuel combustion vary slightly between the methods, as outlined in the below table. The biggest challenge to comparability comes from the units in which these emissions factors are reported. IAI includes mass-based, volume-based, and energy-based values. China NDRC requires users to calculate their own emissions factors according to provided data on mass and volume-based lower calorific values, carbon contents, and oxidation rates. EC does not provide data in consistent units, switching between a mass basis, a volume basis, and an energy basis on an ad hoc basis. Confusingly, even some solid inputs with inconsistent densities, such as petroleum coke, are given emissions factors according to volume. Table 5 illustrates the differences between selected default emissions factors for each method examined, and the implications of these differences for the stationary combustion emission calculation is described in the Case Study.

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[29] China National Development and Reform Commission, "Guidelines for Accounting and Reporting Greenhouse Gas Emissions: China Electrolytic Aluminum Production Enterprises," 3.

[30] Environment Canada, "Aluminium Production: Guidance Manual for Estimating Greenhouse Gas Emissions," 3.

Table 5. Comparison of Default Combustion Emissions Factors for CO_2 by Method [a]

	IAI (tCO_2/TJ) [b]	IAI (tCO_2/unit)	NDRC (tCO_2/TJ)	NDRC (tCO_2/unit)	EC (tCO_2/unit)
Bituminous Coal	94.6	2.441 (t)	89.27	1.747 (t)	2.254 (t) [c]
Petroleum Coke	107	3.017 (t)	100.83	3.228 (t)	3.111 (t)
Diesel	74.1	3.186 (t)	72.59	3.096 (t)	3.250 (t)
Kerosene	71.9	3.149 (t)	70.43	3.152 (t)	3.121 (t)
Heavy Oil	77.4	3.127 (t)	75.82	3.170 (t)	3.219 (t) [d]
Natural Gas	56.1	1.885 (k.NM^3)	61.81	2.406 (k.NM^3)	1.92 (k.NM^3)

Source: Prepared by the authors based on the listed guidelines.

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[a] Denominator unit is given in parentheses when unspecified in heading.

[b] IAI directs users without access to higher tiers of data to use EFs from the GHG Protocol's tool for stationary combustion. Both energy and mass/volume units are provided here.

[c] Ontario value, 1995-2000.

[d] EC provides an EF of 2730 g/L for diesel, 2550 gCO_2/L for kerosene, and 3090 gCO_2/L for heavy oil. These factors have been converted to tons[31] to improve comparability within the table. Oddly, EC reports its EF for petroleum coke as 4200 g/L, using a volume measurement even though petroleum coke is a fine-grained solid with a variable density. A value of 1350 g/L is used for the conversion to a mass basis within this table.[32]

2.7 Mobile Combustion

Emissions from mobile combustion mainly arise from transportation and distribution of materials within the supply chain both onsite and offsite via modes such as ships, trucks, and trains. This includes haulage on mine sites, transportation of raw materials to processing sites, transportation of alumina and other processed materials to primary aluminum producers, transportation of intermediate materials within the facility, and transportation of waste to designated sites.

IAI disclosure level 3 and the IAI Good Practice Guidance on Carbon Footprints, which aim to provide a complete cradle-to-gate carbon footprint for primary aluminum products, calculate mobile combustion emissions by following the GHG Protocol worksheet on emissions from mobile combustion. This tool calculates these emissions using EPA default emissions factors according to distance, fuel source, and vehicle type. IAI 1 and 2 do not consider emissions from transportation of raw goods, intermediate products, or waste.

Environment Canada applies a similar calculation approach, which disaggregates fuel combustion by fuel and vehicle type without directly referencing the GHG Protocol. However, EC discriminates according to where the mobile combustion takes place, counting onsite, process-critical mobile combustion emissions while ignoring offsite mobile combustion emissions. China NDRC simply applies a fuels-based approach, which provides no indication of whether the reported emissions come from fuels consumed through stationary or mobile combustion.

2.8 Emissions from Electricity

Primary aluminum production is inescapably reliant on electricity consumption. Electricity is used both for core processes, such as the electrolysis of alumina into metallic aluminum, as well as auxiliary processes, such as operating cooling and heating equipment and waste management. Electricity is so important to modern aluminum production that smelters are typically sited next to large-scale, inexpensive power sources to ensure affordable access to all the energy they require. Aluminum smelters also frequently incorporate onsite power plants to convert waste heat from processes into steam and even more electricity, for use either onsite or offsite.[33]

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[31] Conversion values obtained from https://www.cbs.nl/en-gb/onze-diensten/methods/definitions/weight-units-energy.

[32] Value obtained from https://www.sciencedirect.com/science/article/abs/pii/S0016236113000835.

[33] Tabereaux, Alton T. and Peterson, Ray D., "Aluminum Production," *Treatise on Process Metallurgy: Industrial Processes*, 2014, 839.

IAI Good Practice Guidance on Carbon Footprints includes onsite generation of electricity and lifecycle emissions of imported electricity in its inventory of emissions from electricity. Emissions calculations for offsite sources apply the GHG Protocol's tool for calculating emissions from purchased electricity and advise estimating CO_2 emissions by multiplying MWh of electricity lost or consumed by a lifecycle emissions factor, including upstream emissions from fuel refining and transportation, construction of energy facilities, and T&D losses. If this value is not known, then IAI advises following an IPCC tier methodology to identify appropriate emissions factors. If possible, users should obtain emissions factors for purchased energy directly from the supplier; if these are unavailable, users should use regional estimates, then national averages. IAI does not provide suggestions on how emissions from construction of energy facilities should be allocated to the emissions footprint of generated power over time. IAI also notes that if energy procurement through the grid is accomplished via a renewable energy certificate (REC) or guarantee of origin confirming the source of power, then the emissions factor can be taken from the certificate. From that perspective, IAI seems to align with the GHG protocol by inviting users to avoid discounting emissions for certificates that are not associated with physical delivery of power, although this is not explicitly stated. Furthermore, users could reduce their reported emissions by using RECs which do not report the full lifecycle emissions from energy production IAI otherwise requires. RECs have enabled reported emissions reductions which do not correspond to emissions reductions in the real world and do not contribute to their stated goal of decarbonizing the power grid.[34] [35] Therefore, both IAI and the GHG Protocol should reassess whether to strengthen their requirements and permit the use of these market-based accounting techniques.

In the case of captive power generation, IAI 3 and the IAI Good Practice Guidance on Carbon Footprints require the inclusion of emissions from upstream fuel processing which should be incorporated into any calculations of emissions intensity, while IAI 1 and 2 do not. China NDRC calculates emissions from electricity by subtracting net sold electricity from net purchased electricity. Emissions factors are reported according to the grid average for the region in which the plant is located, since China's electricity network is divided into seven distinct grids.[36] However, this methodology makes little consideration for self-generation of electricity, even though China NDRC highlights electricity supply as an auxiliary production system in its accounting boundary.

EC's direct emissions-focused methodology takes the opposite approach by excluding emissions from purchased electricity, sold electricity, and electricity transferred within the facility while requiring reporting on emissions from fossil fuel combustion at an onsite power plant. While the EC guidance is meant to contribute to a national inventory rather than providing a complete figure of emissions intensity, excluding indirect emissions hides one of the largest sources of GHG emissions for aluminum – especially since smelters are often constructed adjacent to dedicated power facilities.

All three methods require reporting emissions of CO_2, N_2O, and CH_4 tied to electricity consumption or production. IAI 3, the IAI Good Practice Guidance on Carbon Footprints, and EC additionally require reporting emissions of SF_6, which is used as an electrical insulator for circuit breakers and a cover gas for processes involving electricity. SF_6 can either be consumed over the course of normal operation of equipment or released unintentionally. Even though EC generally does not include fugitive emissions in its reporting, it appears to make an exception for leakage of SF_6. IAI's inclusion of SF_6 is in line with GHG Protocol guidance to include all onsite fugitive emissions sources, but only IAI's PCF for aluminum hydroxide, states that direct emissions from venting of non-CO_2 gases are included.

2.9 Emissions from Imported Materials

IAI 3 and the IAI Good Practice Guidance on Carbon Footprints provide the greatest level of detail and justification for which upstream emissions from input processing to include. According to IAI, a historical impact analysis has demonstrated that production of calcined lime, sodium hydroxide, cathode carbon, aluminum fluoride, coke, and pitch are the only upstream processes which make a material contribution to the emissions intensity of final products. In addition to bauxite and alumina transport, IAI claims that these sources account for "over 90% of non-electricity generation related

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[34] Anders Björn, Shannon M. Lloyd, Matthew Brander and H. Damon Matthews, "Renewable energy certificates allow companies to overstate their emission reductions," *Nature Climate Change* 12 (June 9, 2022): 508-509, https://www.nature.com/articles/s41558-022-01385-7.

[35] Ben Elgin and Sinduja Rangarajan, "What Really Happens When Emissions Vanish," Bloomberg, October 31, 2022, https://www.bloomberg.com/news/features/2022-11-01/intel-p-g-cisco-among-major-companies-exaggerating-climate-progress.

[36] Global Energy Network Institute, Map of Chinese Electricity Grid, http://www.geni.org/globalenergy/library/national_energy_grid/china/chinesenationalelectricitygrid.shtml.

indirect emissions in the aluminum production chain."[37] IAI also includes N_2O, CH_4, and SF_6 emissions from imported materials, the latter of which indicates that IAI is considering upstream fugitive emissions.[38]

Similarly to its approach to upstream emissions from electricity, EC explicitly avoids including indirect emissions tied to materials imported from offsite. China NDRC also does not include emissions from imported materials, although it does include emissions from imported electricity.

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[37] International Aluminium Institute, "Aluminium Carbon Footprint Technical Support Document v1.0," 9.

[38] International Aluminium Institute, "Good Practice Guidance for Calculation of Primary Aluminium and Precursor Product Carbon Footprints," 9.

Table 6. Overview of System Boundaries

	China NDRC	EC	IAI Level 1	IAI Level 2	IAI Level 3
Direct Emissions					
Electricity Generation	Yes	Yes	Yes	Yes	Yes
Anode Prebaking	No	Yes	Yes	Yes	Yes
Smelting Furnace	Yes	Yes	Yes	Yes	Yes
Ingot Casting	Unspecified	Unspecified	Yes	Yes	Yes
Dross Processing	Unspecified	Unspecified	No	No	Yes
Remelting of Scrap	No	No	Yes	Yes	Yes
Onsite Transportation	Unspecified	Yes	No	No	Yes
Calcination	Yes	No	No	No	Yes
Anode Consumption	Yes	Yes	Yes	Yes	Yes
Anode Effect	Yes	Yes	Yes	Yes	Yes
Fugitive SF_6 Emissions	No	Yes	No	No	Yes
Fugitive HFC Emissions	No	Yes	No	No	No
Management of Waste	Unspecified	Unspecified	No		Yes
Indirect Emissions					
Imported Electricity	Yes	No	Yes	Yes	Yes
Bauxite Mining	No	No	No	Yes	Yes
Alumina Refining	No	No	No	Yes	Yes
Offsite Transportation	No	No	No	No	Yes
Upstream Calcination	No	No	No	No	Yes
Sodium Hydroxide Production	No	No	No	No	Yes
Cathode Carbon Production	No	No	No	No	Yes
Aluminum Fluoride Production	No	No	No	No	Yes
Coke Production	No	No	No	No	Yes
Pitch Production	No	No	No	No	Yes
Fuel Production	No	No	No	No	Yes
Upstream Fugitive Emissions	No	No	No	No	Unspecified [a]

Source: Prepared by the authors based on the listed guidelines.

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[a] IAI includes cradle-to-gate emissions from imported materials, including CO_2, SF_6, CH_4, and N_2O emissions. SF_6 emissions are likely have been vented unintentionally, since SF_6 is used as a cover gas and an electrical insulator. However, IAI does not specifically state whether these CH_4 emissions would include fugitive emissions.

2.10 Emissions from Imported Materials

Unique among the methodologies, IAI 3 and the IAI Good Practice Guidance on Carbon Footprints provide a harmonized and internally consistent means to calculate emissions for both intermediate and final products within the primary aluminum supply chain, with separate PCFs for bauxite and other ores, aluminum hydroxide, alumina, and primary aluminum. This level of detail provided for each intermediate good means that greater detail is included on the various emissions sources which must be calculated and recorded. These also uniquely require reporting emissions not just from processing of upstream inputs, but from processing of waste products as well, which must be included for each PCF. Table 6 provides a summary of the emission sources included under each method, and a complete overview of the emission category disclosure requirements for each separate PCF under IAI's Good Practice Guidance on Carbon Footprints is provided in Appendix I.

2.11 Emissions Allocation

Under certain carbon accounting methodologies, emissions credits are assigned to account for theoretical reductions of emissions as the result of a reporting entity's actions. For some credits, such as those awarded for exports of intermediate goods which were purchased in excess, reallocating emissions tied to them is a credible and legitimate adjustment to emissions intensity. Others, such as credits for the export of CO_2 to soft drink companies, rely on the existence of a hypothetical emissions baseline in an entirely separate industry – a counterfactual which is difficult or even impossible to verify.

The IAI Good Practice Guidance on Carbon Footprints is the only method to approach providing an allocation method for emissions from production of alumina, which can be sold in its calcined form for use by other aluminum smelters, and aluminum hydrate, which can be sold prior to calcination to users in other industries. IAI instructs users to calculate and separate emissions associated with alumina and hydrate which are not processed further within the facility. But IAI does not explicitly call for these emissions to be credited back, noting only that "the sum of allocated inputs and outputs of a unit process shall be equal to the inputs and outputs of the unit process before allocation."[39]

China NDRC allows electricity which is sold back to the grid to be netted out of the final emissions calculation without specifying a credit emissions factor. The IAI Good Practice Guidance on Carbon Footprints recommends following the "efficiency method" for sales of captive power, which involves imputing an emissions factor from the fuel requirements for the heat and steam used to produce this power, reporting these emissions and separately and deducting these emissions from those of the internal energy consumption. This deduction can be contrasted with the GHG Protocol Guidelines for Quantifying GHG Reductions from Grid-Connected Electricity Projects, which requires these reductions to be calculated according to an adjusted baseline of displaced grid emissions.[40] Both of these approaches are at apparent odds with the GHG Protocol Corporate Standard, which does not permit netting out emissions associated with the sale of autogenerated electricity from direct emissions.[41]

Finally, all methods avoid other potential sources of credit emissions. All methods calculate emissions from electrolysis according to net anode consumption to accounting for the incomplete consumption of anodes and the reuse of anode butts, but no method specifies whether this net consumption includes purchase and sale of anodes as well. Other aluminum byproducts, such as red mud and salt slag, have potential applications within other industries, but these typically lack a practical use case strong enough to justify credit emissions or face legal barriers to their reuse. No provision is made for crediting of CO_2 emissions which are delivered to CCU or CCS projects.

3 Case Study

To illustrate the reporting outcomes of these different methodologies, CCSI constructed a simplified aluminum smelter producing 200,000 tons of product per year through a PFPB process. The primary aluminum producer imports all its alumina and electricity, produces 92,000 tons of anodes per year for onsite consumption, and exports electricity which it generates onsite, reporting the following activity data:

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[39] International Aluminium Institute, "Good Practice Guidance for Calculation of Primary Aluminium and Precursor Product Carbon Footprints," 18.

[40] Derik Broekhoff, "The Greenhouse Gas Protocol: Guidelines for Quantifying GHG Reductions from Grid-Connected Electricity Projects" (World Resources Institute/World Business Council for Sustainable Development, December 2005), 21, https://files.wri.org/d8/s3fs-public/pdf/ghgprotocol-electricity.pdf.

[41] Janet Ranganathan, Laurent Corbier, Pankaj Bhatia, Simon Schmitz, Peter Gage, and Kjell Oren, "The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard" (World Resources Institute/World Business Council for Sustainable Development, March 2004), 27, https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf.

Table 7. Case Study Activity Data

Input	Anode Baking	Electrolysis	Casting	Export	Total Imports	Net Imports
Heavy Oil (t)	3,400	0	200	N/A	3,600	3,600
Diesel Oil (t)	0	0	80	N/A	80	80
Natural Gas (k.Nm^3)	9,400	0	4,200	N/A	13600	13600
Imported Electricity (mWh)	22,200	2,813,200	10,600	300,000	2,846,000	2,546,000
Alumina (t)	383,800	0	0	N/A	383,800	383,800
Petroleum Coke (t	135,000	0	0	N/A	135,000	135,000
Pitch (t)	29,200	0	0	N/A	29,200	29,200
Cathode Carbon (t)	0	1,200	0	N/A	1,200	1,200
Aluminum Fluoride (t)	0	3,200	0	N/A	3,200	3,200

Source: Compiled by the authors according to the 2017 IAI Life Cycle Inventory.

The plant's upstream alumina supplier reports a carbon footprint of .547 tCO_2/t product on the basis of its own emissions measurement. Additionally, the 100% natural gas-based regional grid has an emissions intensity of .458 tCO_2/mWh. The plant reports an average daily anode effect duration of .1 minutes per smelting pot and has measured its annual green anode tonnage as 194,667 t. Applying the methods examined in this study would yield the following reporting:

Table 8. Case Study Results

All figures given in tCO_2e	EC	IAI 1	IAI 2	IAI 3	China NDRC
Imported Materials	N/A	N/A	209,883 t	432,220 t	N/A
Onsite and Stationary Combustion	457,945 t	444,443 t	444,443 t	444,560 t	480,161 t
Offsite Transport	N/A	N/A	N/A	44,237 t	N/A
Anode/Cathode Baking	376,948 t	377,667 t	377,667 t	382,593 t	N/A
Anode Consumption	327,888 t	329,237 t	329,237 t	329,237 t	329,237 t
Anode Effect	21,252 t	59,360 t	59,360 t	59,360 t	21,221 t
Electricity Consumption	N/A	1,323,437 t	1,323,437 t	1,323,437 t	1,186,037 t
Waste Disposal	N/A	N/A	N/A	1883 t	N/A
Total	1,184,033 t	2,534,144 t	2,744,027 t	3,017,527 t	2,016,656 t

Source: Calculated by the authors according to the listed guidelines.

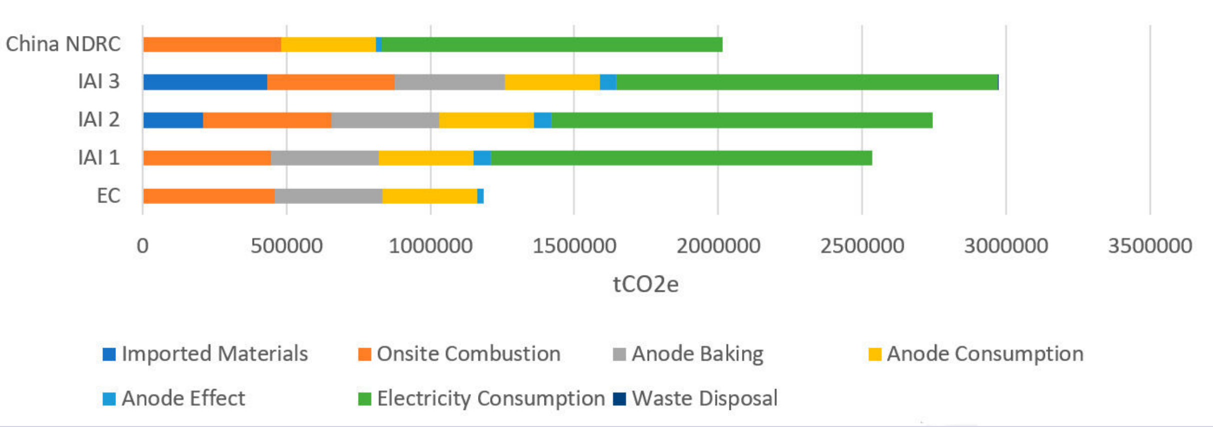


Figure 4. Case Study Results

Source: Prepared by the authors based on calculations from the case study.

Aluminum reporting methods apply a carbon mass balance approach to process emissions, leading to relatively similar outcomes despite differences in default values between the methods. For PFC emissions from electrolysis, EC and IAI require some justified estimation of anode effect duration to be included in activity data at the absolute minimum. Only China NDRC allows a Tier 1-style estimation of PFC emissions according to averages per ton of product, an approach which was not applied here to maintain comparability.

However, the impact of inconsistent system boundaries is on full display. For this plant, imported electricity makes the greatest single contribution to emissions. IAI records this in full, and China NDRC subtracts out the plant's exported electricity to record the plant's net electricity consumption, but EC does not include indirect emissions from electricity consumption. As a result, using the EC method would allow this plant to cut its reported emissions by half. China NDRC's exclusion of anode baking from its emissions reporting substantially reduces the reported intensity, and IAI 2's inclusion of emissions from imported alumina adds a significant quantity of reported emissions in comparison with China NDRC, IAI 1, and EC.

4 Conclusion

The consolidation of most (but not all) GHG accounting in the aluminum sector behind an IAI methodology with firmly defined system cradle to gate boundaries that strongly emphasizes the use of primary data represents a partial success in efforts to move towards more cohesive, rigorous GHG accounting. However, the IAI Good Practice Guidance on Carbon Footprints still needs improvement.

First and foremost, like the other methods examined, IAI does not provide sufficient clarity around when semi-fabrication processes should be assigned to primary aluminum production and when they should be assigned to secondary aluminum production. Primary aluminum cast-houses are increasingly involved in producing the Value-Added Products (VAPs) which have been traditionally assigned to secondary aluminum production, but no method has specified how to account for emissions from secondary production and semi-fabrication. As the aluminum sector decarbonizes and more scrap is recycled within these processes, filling this accounting gap will become increasingly important to ensure that sectoral incentives remain aligned with decarbonization priorities.

Stricter and more granular guidance should also be provided on accounting for incorporation of scrap of all types into final products from the cast-house. EC and China NDRC do not touch on the issue of scrap at all. IAI includes a transparency requirement for usage of scrap as an input which requires reporting of the percentage of both pre-consumer and post-consumer scrap. However, IAI neither details how carbon footprints should be calculated for each form of scrap nor how a final carbon footprint should be calculated according to the quantities of each form of input. IAI's internal reference document provides a range of potential methods for attaining these values, but as the ISO and European standards behind these methods are in conflict and the aluminum industry has not reached consensus on which method to use, IAI has declined to make a single recommendation. IAI should settle on one method and publicize it as soon as possible to avoid the inadvertent double-counting and unreported emissions resulting from scrap buyers and sellers applying different allocation methods. IAI should also continue advancing its research into how producers can avoid commingling pre-consumer and post-consumer scrap and develop frameworks to prevent commingling from influencing carbon footprint accounting.

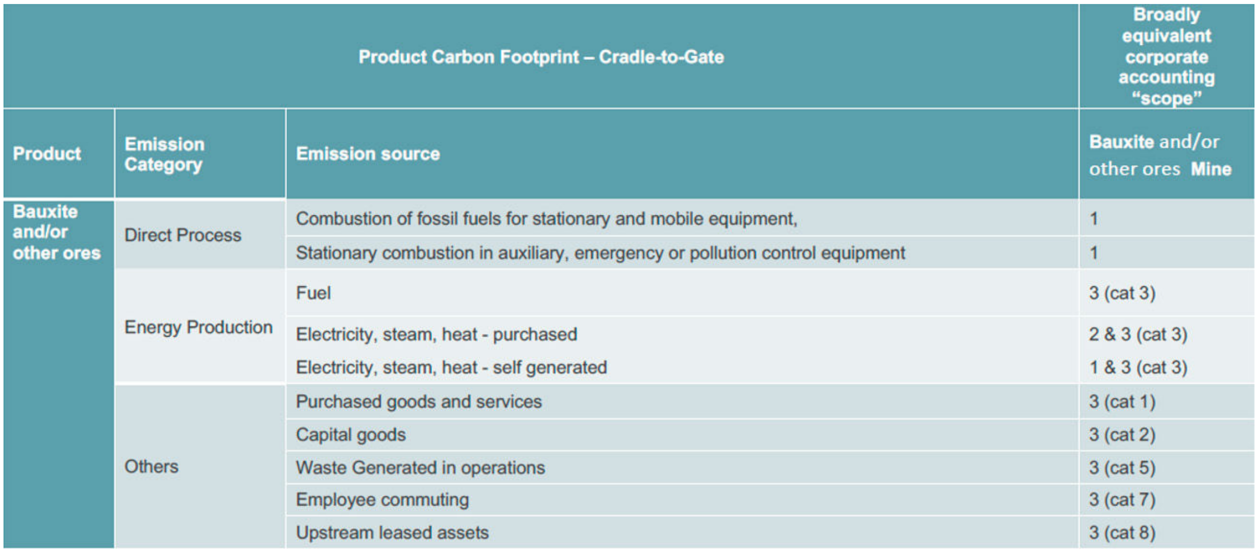
The outsized importance of electricity in primary aluminum production means that aligning practices for calculating indirect emissions from electricity consumption with best practices is particularly important. As mentioned, EC avoids including this essential emissions source. China NDRC calculates indirect emissions according to grid-wide regional emissions intensity averages, which fails to capture substantial variations in emissions intensity according to the time of year or day and discourages producers from seeking out less GHG-intensive power sources. China NDRC also allows producers to subtract electricity they sell back to the grid, while IAI allocates emissions from sold electricity according to estimates of the fuel energy required to produce it. Meanwhile, GHG Protocol product guidance maintains its own method for calculating emissions reductions from sold electricity by estimating how much energy from the power grid is displaced. These varied approaches demonstrate that no defined best practices for allocation of sold electricity actually exist. Furthermore, IAI specifies an approach to calculating life cycle emissions factors for imported electricity whose consequence is to elevate certain low-carbon sources of energy over others (e.g., inclusion of emissions from construction of energy facilities provides an advantage to solar and wind over hydropower when dam construction relies on GHG-intensive concrete). IAI also does not specify how upfront emissions from construction of energy infrastructure should be allocated to the carbon footprint of energy generated, does not provide meaningful safeguards for ensuring that emissions factors claimed via RECs correspond to real reductions in the GHG intensity of the local grid, and does not require that emissions reporting from RECs claimed under their methodology follow the life cycle approach applied elsewhere in their guidelines.

Properly accounting for and reporting both direct and indirect fugitive emissions remains a challenge for all methods examined. EC and IAI call for direct fugitive emissions to be reported, but without providing a recommended approach. Differently from other methods, IAI also requires the inclusion of upstream fugitive emissions, but does not give guidance on how to calculate them. CH_4 emissions from the extraction and refining processes that help produce petroleum coke make a substantial contribution to the upstream footprint of carbon anode production, not to mention fugitive CH_4 emissions associated with the mining of coal for power generation, and future research should focus on quantifying these fugitive emissions so aluminum producers can properly include them within their own PCFs.

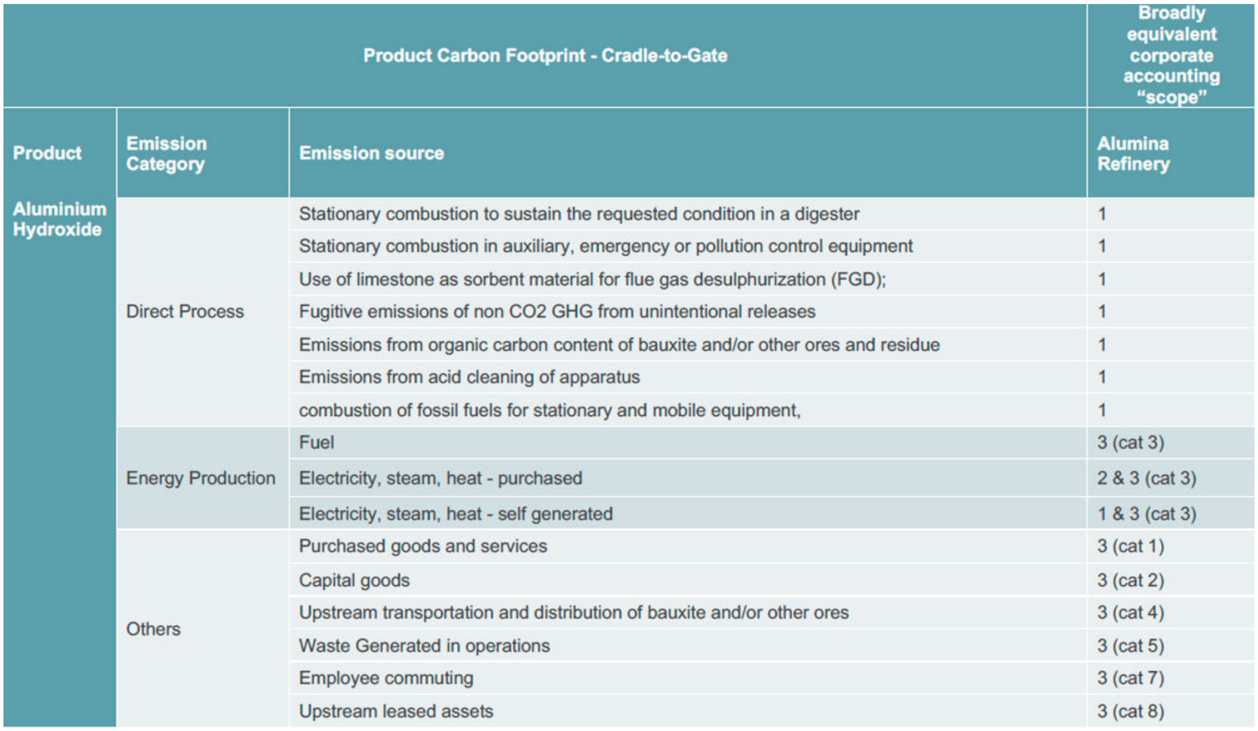
Following research into PFC sources such as LVAEs which went unmeasured under older estimation methods, international guidance detailed under the 2019 IPCC revision has strongly encouraged direct measurement of these emissions. IAI has issued new best practice guidelines for measuring PFC emissions to reflect this, but neither China NDRC nor EC have issued similar updates. This leaves their guidance out of alignment with international standards. Regional and national emissions regulations should also be revised to comply with the latest science. For instance, European regulations governing PFC emissions reporting under EN-19694-4 date back to 2016 and as such do not reflect this update.

Finally, the aluminum sector's approach to GHG accounting largely avoids emissions credits for intermediate and waste products which could reduce emissions elsewhere. Process gases like CO_2 could be captured and either used in other industries or permanently stored, but no method allows emissions credits to be claimed for either of these activities. This reduces the risk of identifying an inappropriate counterfactual for these claimed reductions, as well as of inadvertently double counting reductions already allotted to other sectors. While more sophisticated life cycle analysis tools could potentially enable such crediting in the future, this relatively conservative approach could serve as a model for ensuring decarbonization takes place within the supply chain itself for all metals industries while avoiding disputes between industries over the rights to claim emissions reductions.

Appendix I – PCF Disclosure Requirements under IAI Guidelines

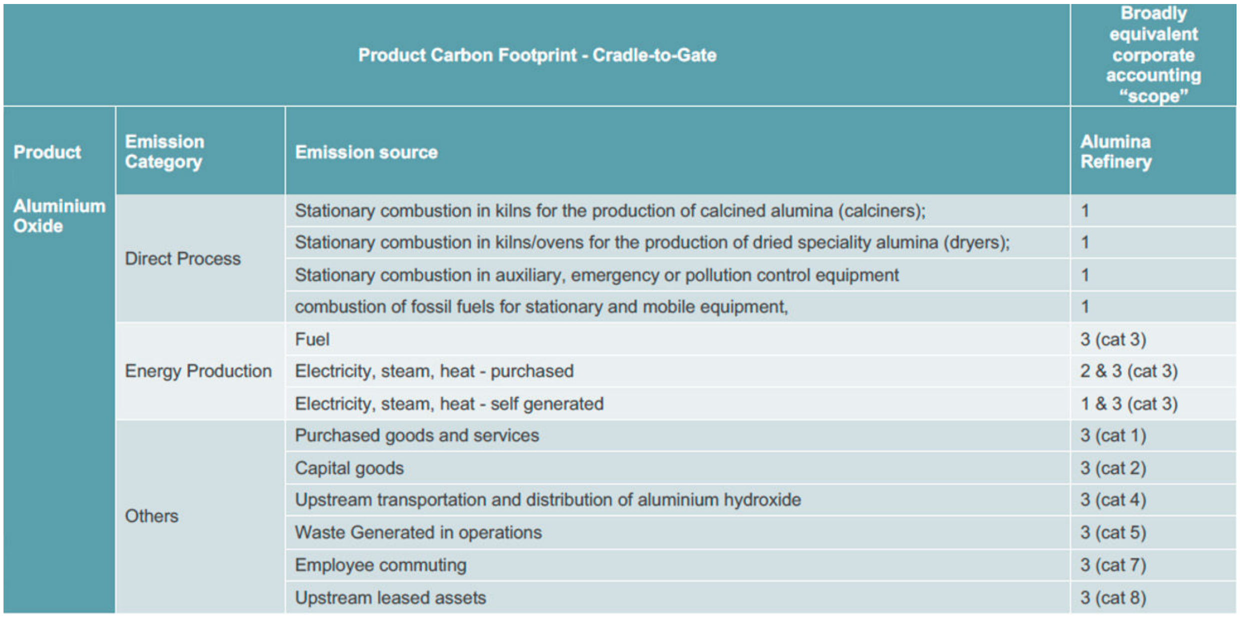


Product Carbon Footprint – Cradle-to-Gate			Broadly equivalent corporate accounting “scope”
Product	**Emission Category**	**Emission source**	**Bauxite** and/or other ores **Mine**
Bauxite and/or other ores	Direct Process	Combustion of fossil fuels for stationary and mobile equipment,	1
		Stationary combustion in auxiliary, emergency or pollution control equipment	1
	Energy Production	Fuel	3 (cat 3)
		Electricity, steam, heat - purchased	2 & 3 (cat 3)
		Electricity, steam, heat - self generated	1 & 3 (cat 3)
	Others	Purchased goods and services	3 (cat 1)
		Capital goods	3 (cat 2)
		Waste Generated in operations	3 (cat 5)
		Employee commuting	3 (cat 7)
		Upstream leased assets	3 (cat 8)

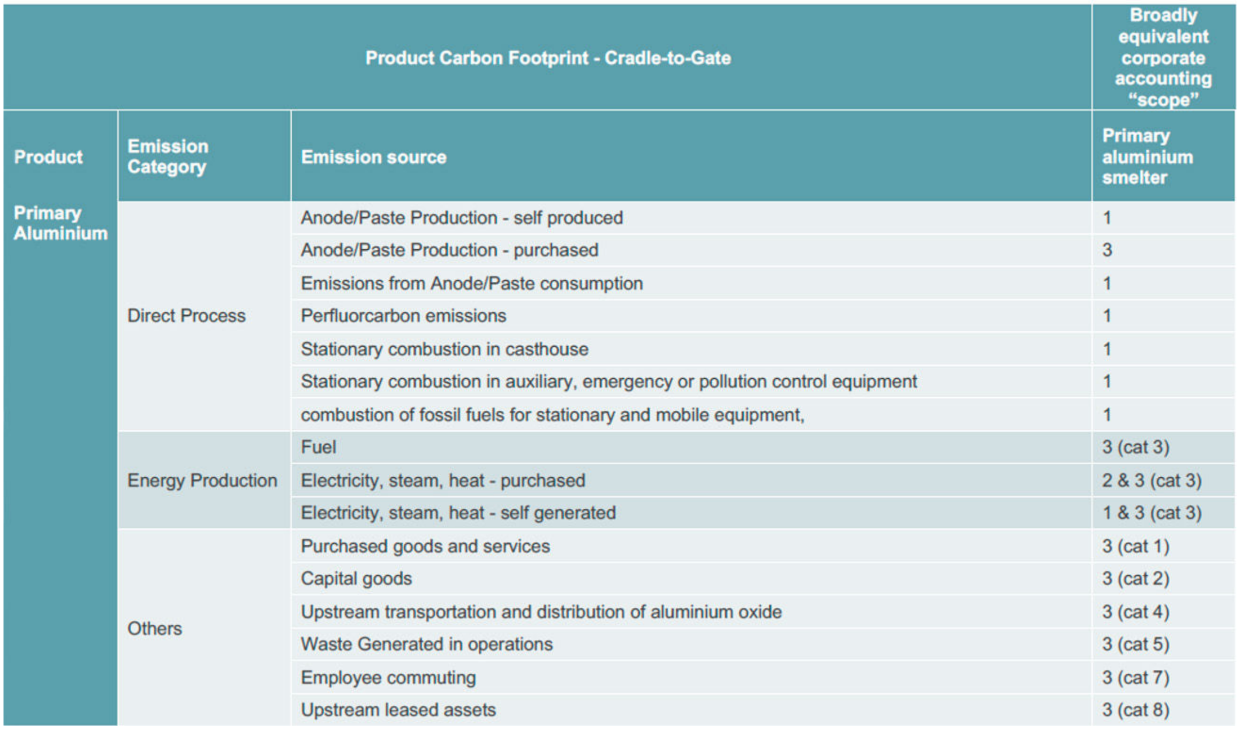


Product Carbon Footprint - Cradle-to-Gate			Broadly equivalent corporate accounting “scope”
Product	**Emission Category**	**Emission source**	**Alumina Refinery**
Aluminium Hydroxide	Direct Process	Stationary combustion to sustain the requested condition in a digester	1
		Stationary combustion in auxiliary, emergency or pollution control equipment	1
		Use of limestone as sorbent material for flue gas desulphurization (FGD);	1
		Fugitive emissions of non CO2 GHG from unintentional releases	1
		Emissions from organic carbon content of bauxite and/or other ores and residue	1
		Emissions from acid cleaning of apparatus	1
		combustion of fossil fuels for stationary and mobile equipment,	1
	Energy Production	Fuel	3 (cat 3)
		Electricity, steam, heat - purchased	2 & 3 (cat 3)
		Electricity, steam, heat - self generated	1 & 3 (cat 3)
	Others	Purchased goods and services	3 (cat 1)
		Capital goods	3 (cat 2)
		Upstream transportation and distribution of bauxite and/or other ores	3 (cat 4)
		Waste Generated in operations	3 (cat 5)
		Employee commuting	3 (cat 7)
		Upstream leased assets	3 (cat 8)

Source: Adapted from International Aluminium Institute, “Good Practice Guidance for Calculation of Primary Aluminium and Precursor Product Carbon Footprints,” 29-30.



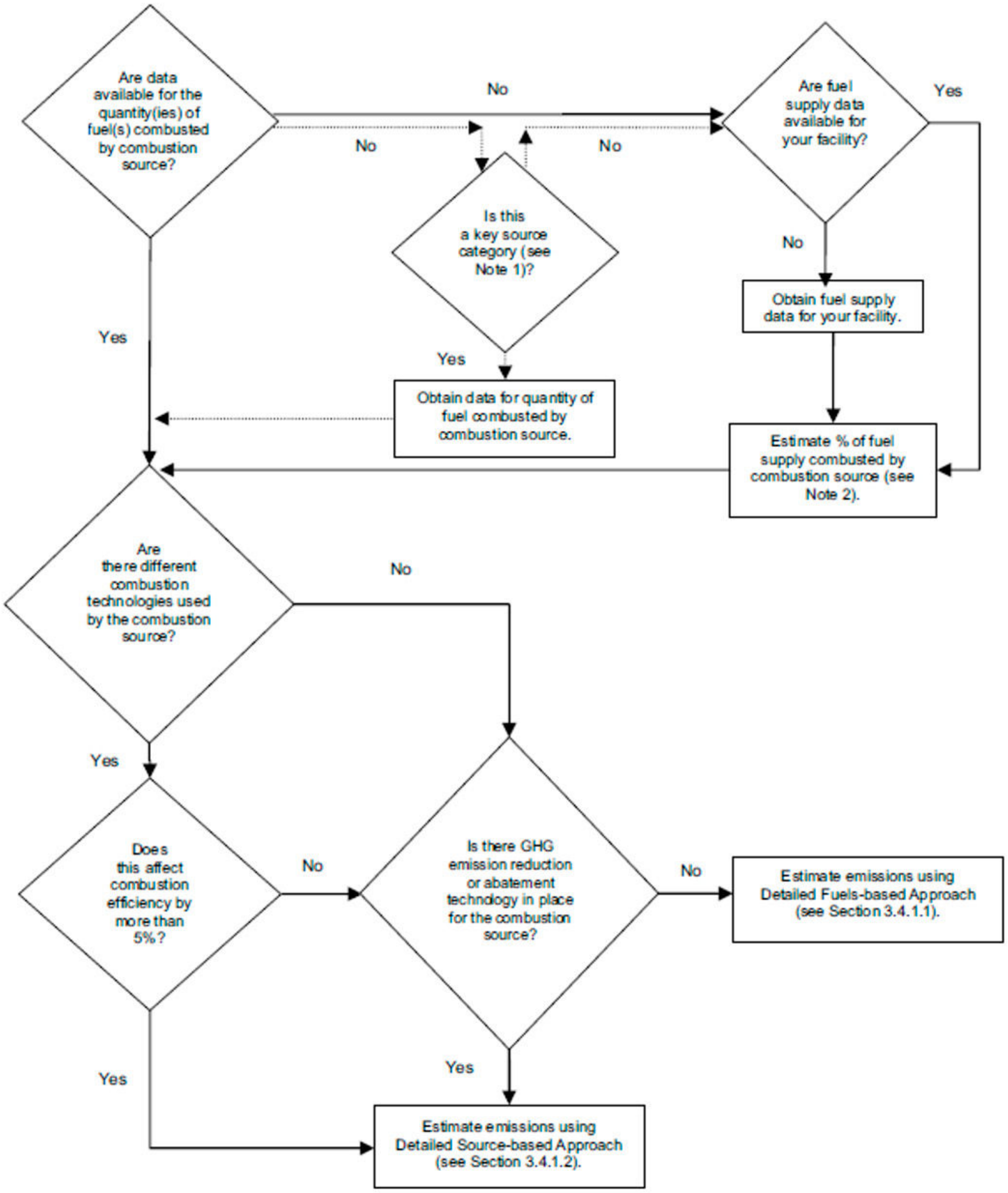
Product Carbon Footprint - Cradle-to-Gate			Broadly equivalent corporate accounting “scope”
Product	**Emission Category**	**Emission source**	**Alumina Refinery**
Aluminium Oxide	Direct Process	Stationary combustion in kilns for the production of calcined alumina (calciners);	1
		Stationary combustion in kilns/ovens for the production of dried speciality alumina (dryers);	1
		Stationary combustion in auxiliary, emergency or pollution control equipment	1
		combustion of fossil fuels for stationary and mobile equipment,	1
	Energy Production	Fuel	3 (cat 3)
		Electricity, steam, heat - purchased	2 & 3 (cat 3)
		Electricity, steam, heat - self generated	1 & 3 (cat 3)
	Others	Purchased goods and services	3 (cat 1)
		Capital goods	3 (cat 2)
		Upstream transportation and distribution of aluminium hydroxide	3 (cat 4)
		Waste Generated in operations	3 (cat 5)
		Employee commuting	3 (cat 7)
		Upstream leased assets	3 (cat 8)



Product Carbon Footprint - Cradle-to-Gate			Broadly equivalent corporate accounting “scope”
Product	**Emission Category**	**Emission source**	**Primary aluminium smelter**
Primary Aluminium	Direct Process	Anode/Paste Production - self produced	1
		Anode/Paste Production - purchased	3
		Emissions from Anode/Paste consumption	1
		Perfluorcarbon emissions	1
		Stationary combustion in casthouse	1
		Stationary combustion in auxiliary, emergency or pollution control equipment	1
		combustion of fossil fuels for stationary and mobile equipment,	1
	Energy Production	Fuel	3 (cat 3)
		Electricity, steam, heat - purchased	2 & 3 (cat 3)
		Electricity, steam, heat - self generated	1 & 3 (cat 3)
	Others	Purchased goods and services	3 (cat 1)
		Capital goods	3 (cat 2)
		Upstream transportation and distribution of aluminium oxide	3 (cat 4)
		Waste Generated in operations	3 (cat 5)
		Employee commuting	3 (cat 7)
		Upstream leased assets	3 (cat 8)

Source: Ibid., 31-32.

Appendix II – Environment Canada Decision Trees

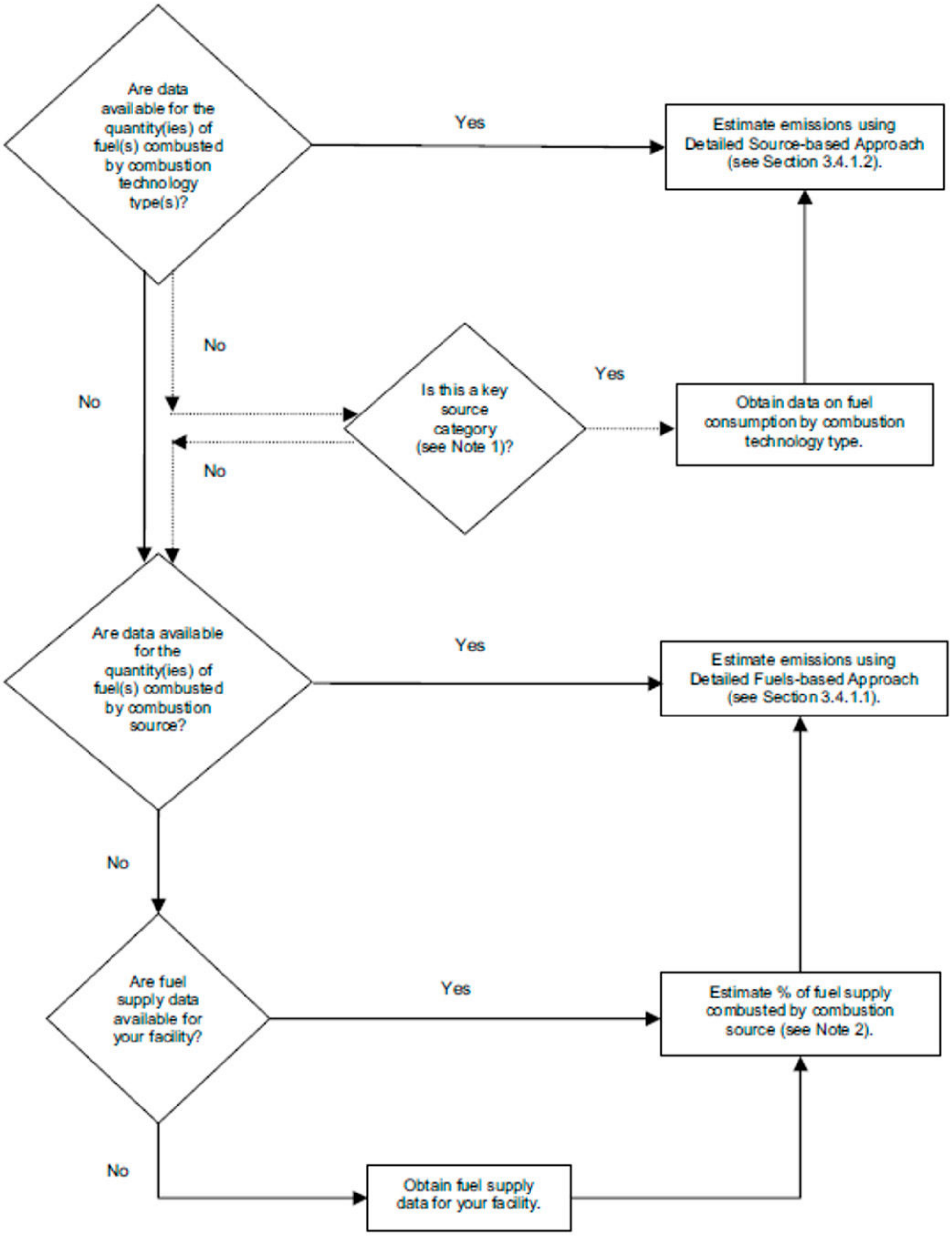


Note 1: From the IPCC Guidelines (IPCC, 1997), a *key source category* is one that is prioritized within the national GHG inventory system because its estimate has a significant influence on a country's total inventory of direct GHG emissions in terms of the absolute level of emissions, the trend in emissions or both. For a facility, a similar definition can be used, where a key source category is one that is prioritized within the facility's GHG inventory system. For further details on this aspect, see Section 3.5. This step in the decision tree can be ignored until your facility has a GHG inventory for several (at least three to five) inventory years.

Note 2: Total fuel supply data may include quantities of fuel that are used for non-energy purposes (e.g. feedstock material). It is necessary to subtract such quantities of fuel from total fuel supplies in order to determine quantities of fuel combusted for the purpose of generating energy.

Figure 5. Decision Tree for Selecting a Method for Estimating CO_2 Emissions from Stationary Fuel Combustion

Source: Adapted from Environment Canada, "Aluminium Production: Guidance Manual for Estimating Greenhouse Gas Emissions," 14.

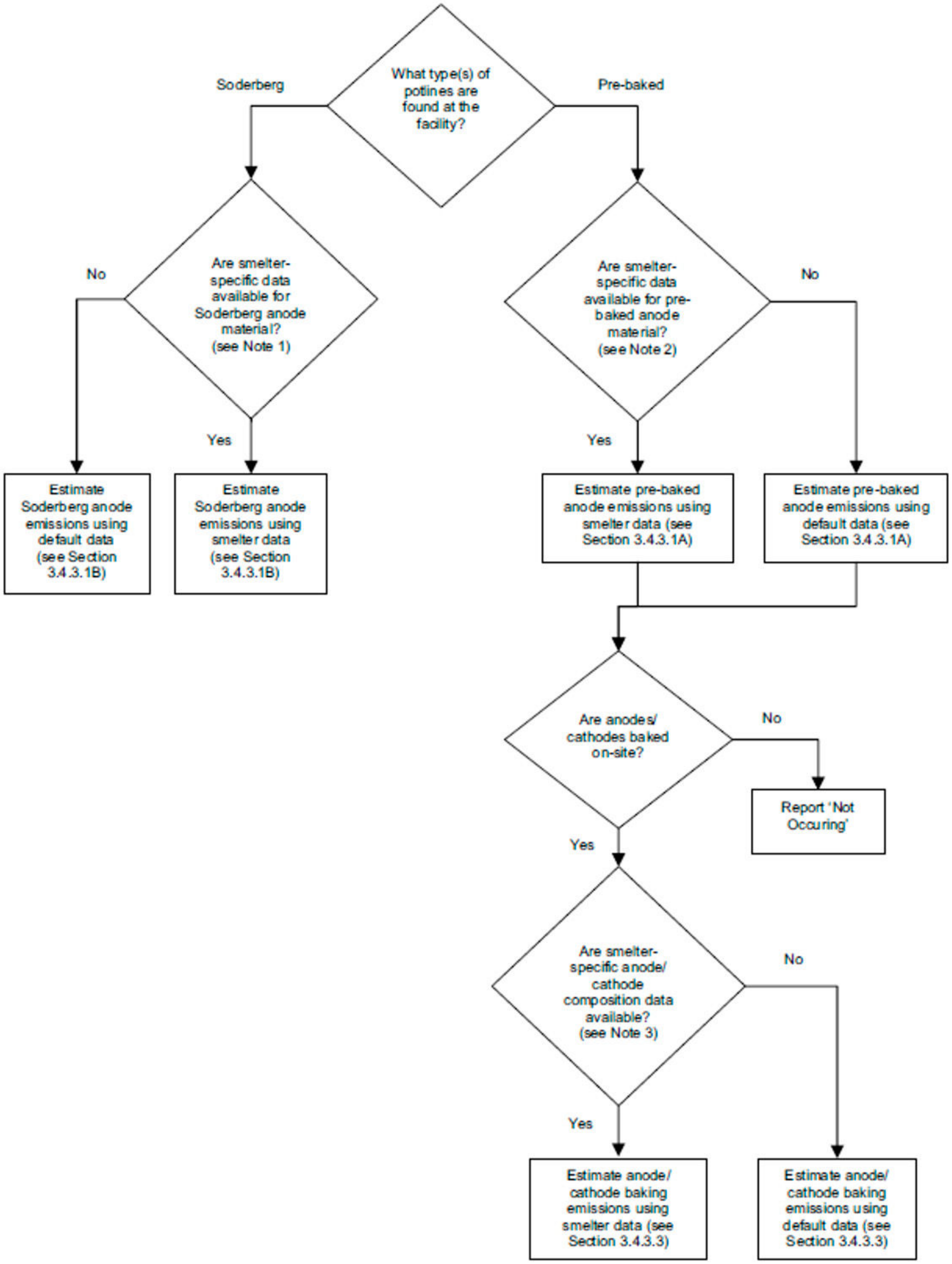


Note 1: From the IPCC Guidelines (IPCC, 1997), a key source category is one that is prioritized within the national GHG inventory system because its estimate has a significant influence on a country's total inventory of direct GHG emissions in terms of the absolute level of emissions, the trend in emissions or both. For a facility, a similar definition can be used, where a key source category is one that is prioritized within the facility's GHG inventory system. For further details on this aspect, see Section 3.5. This step in the decision tree can be ignored until your facility has a GHG inventory for several (at least three to five) inventory years.

Note 2: Total fuel supply data may include quantities of fuel that are used for non-energy purposes (e.g. feedstock material). It is necessary to subtract such quantities of fuel from total fuel supplies in order to determine quantities of fuel combusted for the purpose of generating energy.

Figure 6. Decision Tree for Selecting the Method for Estimating CH_4 and N_2O Emissions from Stationary Fuel Combustion

Source: Ibid., 15.



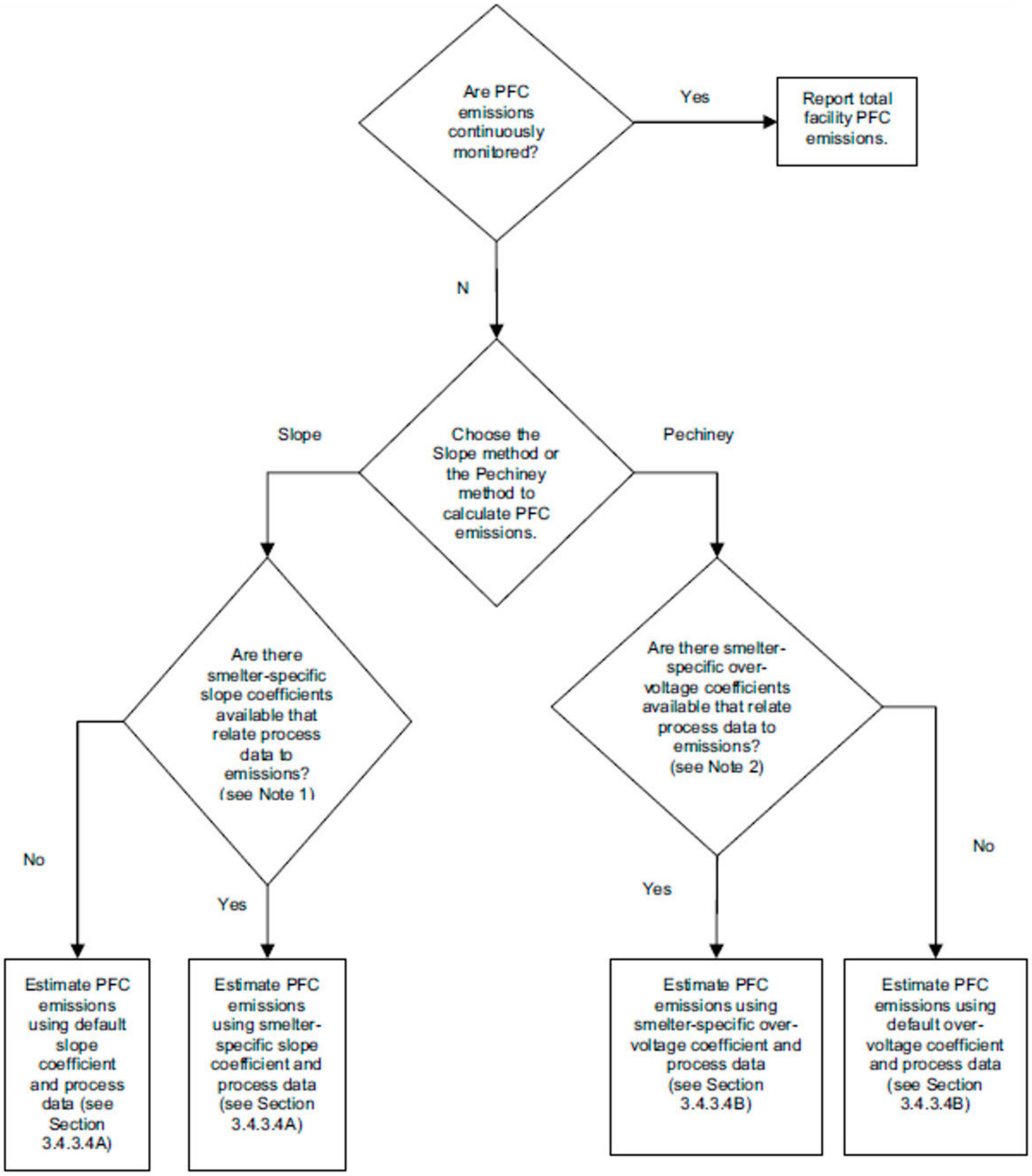
Note 1: Smelter-specific data refers to paste consumed per tonne of aluminium, benzene soluble matter emitted per tonne of aluminium,% binder content in paste, % impurities in pitch and calcinated coke.

Note 2: Smelter-specific data refers to net carbon consumed per tonne of aluminium, % impurities in baked anodes (e.g. sulphur, ash, etc.)

Note 3: Smelter-specific data refers to % impurities in packing coke, pitch content in green anodes/cathodes, % hydrogen in pitch.

Figure 7. Decision Tree for Selecting the Method for Estimating CO_2 Emissions from Anode Consumption and Anode/Cathode Baking

Source: Ibid., 16.



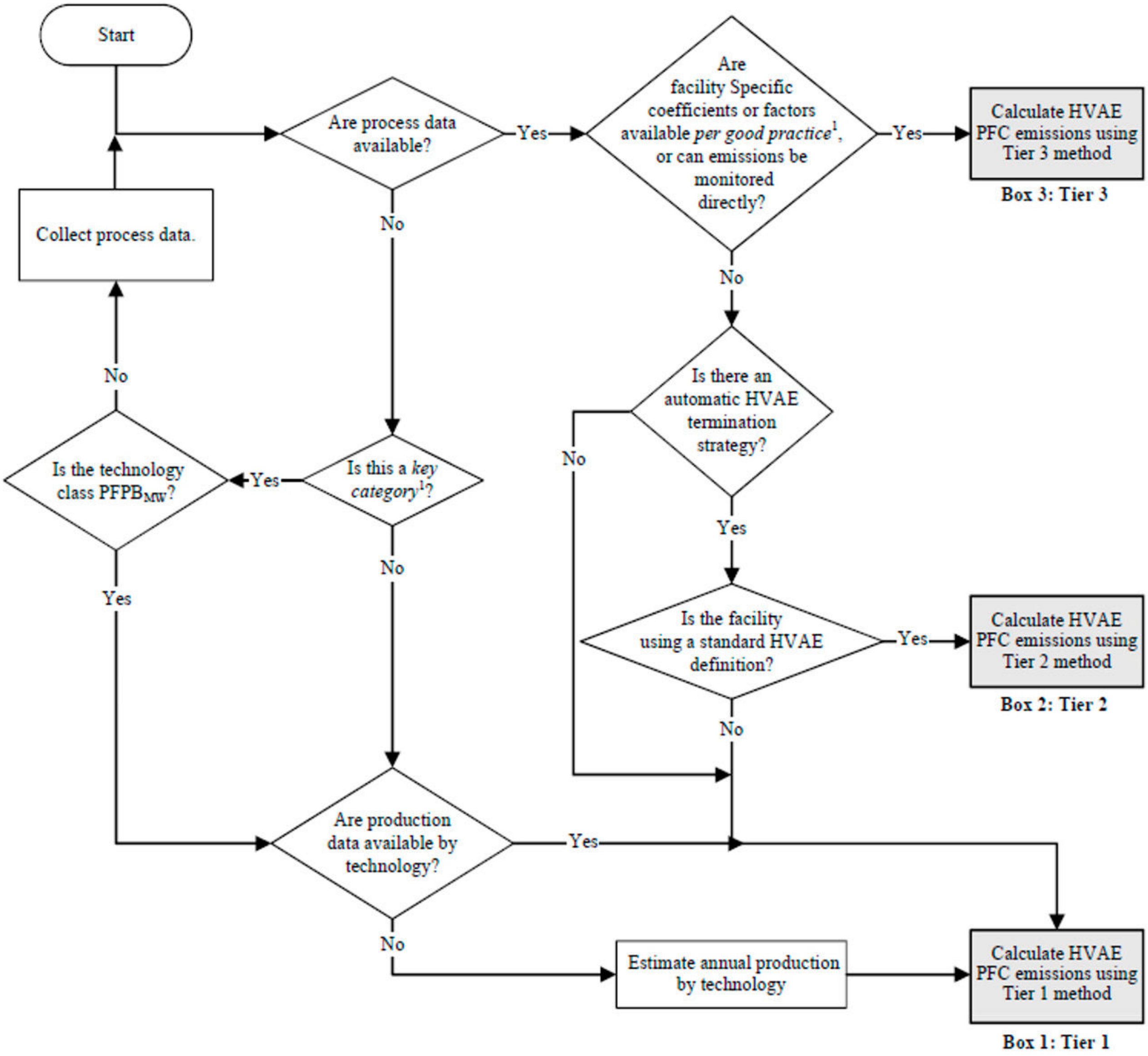
Note 1: "Process data" refers to anode effect frequency (number of anode effects per pot per day) and anode effect duration (in minutes).

Note 2: "Process data" refers to anode effect over-voltage (in millivolts per pot per day).

Figure 8. Decision Tree for Selecting the Method for Estimating PFC Emissions from Anode Effects (or Anode Events)

Source: Ibid., 17.

Appendix III – IPCC PFC Measurement Decision Trees



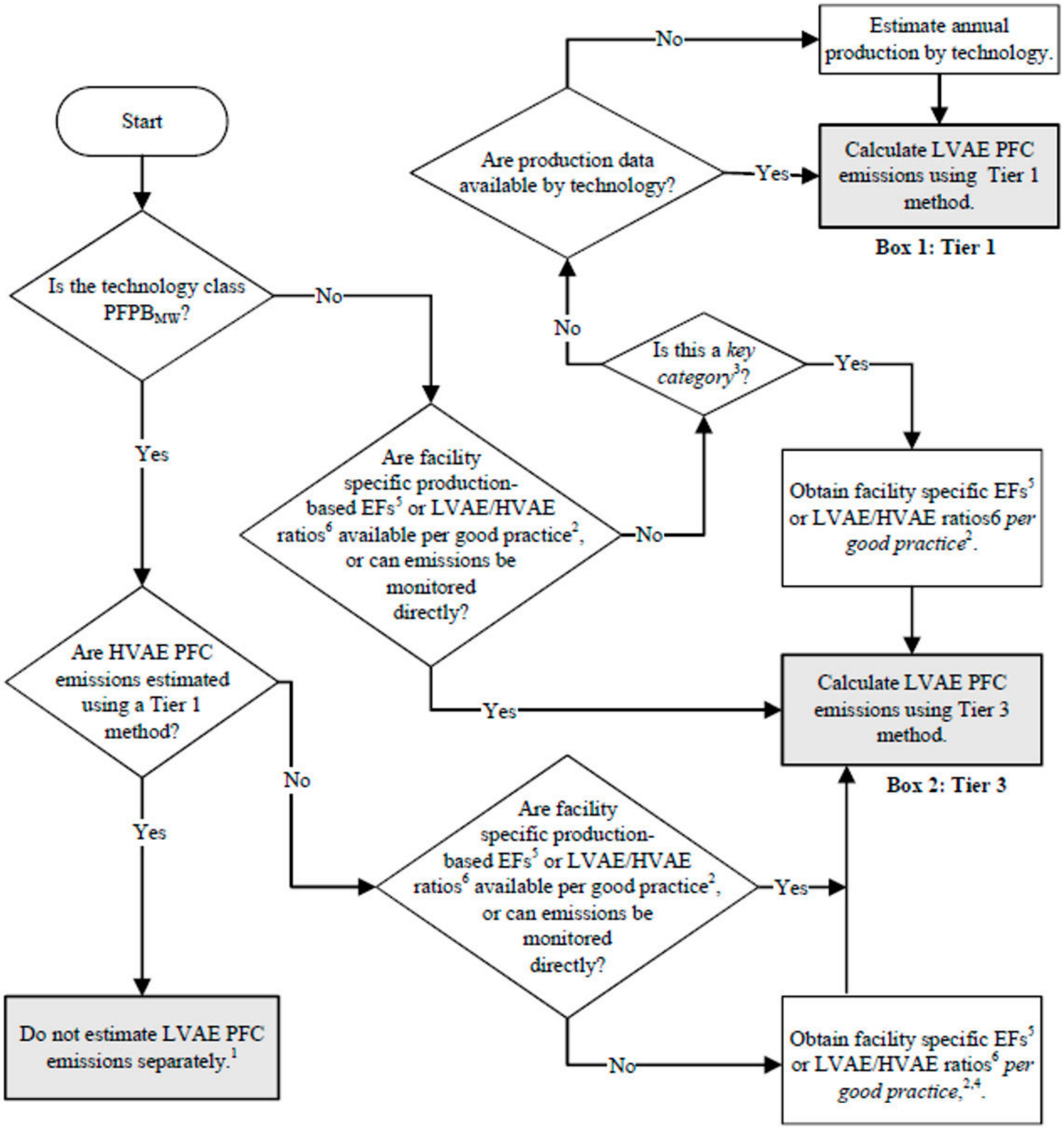
Notes:

[1] *Good practices* for obtaining facility specific PFC emission coefficients are detailed in the Protocol for Measurement of Tetrafluoromethane (CF_4) and Hexafluoroethane (C_2F_6) Emissions from Primary Aluminum Production (US Environmental Protection Agency & International Aluminium Institute 2008).

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

Figure 9. Decision Tree for Calculation of HVAE-related PFC Emissions from Primary Aluminum Production

Source: "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories," Chapter 4: Metal Industry Emissions, 44.



Notes:

[1] LVAE PFC emissions are already accounted for in the Tier 1 default HVAE EF for $PFPB_{MW}$.

[2] *Good practices* for obtaining facility specific PFC emission coefficients are detailed in the Protocol for Measurement of Tetrafluoromethane (CF_4) and Hexafluoroethane (C_2F_6) Emissions from Primary Aluminium Production (US Environmental Protection Agency & International Aluminium Institute 2008).

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

[4] Any $PFPB_{MW}$ facilities employing facility-specific coefficients for HVAE emissions are likely to have the necessary data to obtain facility-specific coefficients or ratios for LVAE emissions.

[5] To use the facility-specific *production-based EF* method (Equation 4.27c), metal production data from the facility must be available.

[6] To use the facility-specific *LVAE/HVAE ratio* method (Equation 4.27d), HVAE emissions must be estimated first.

Figure 10. Decision Tree for Calculation of LVAE-related PFC Emissions from Primary Aluminum Production

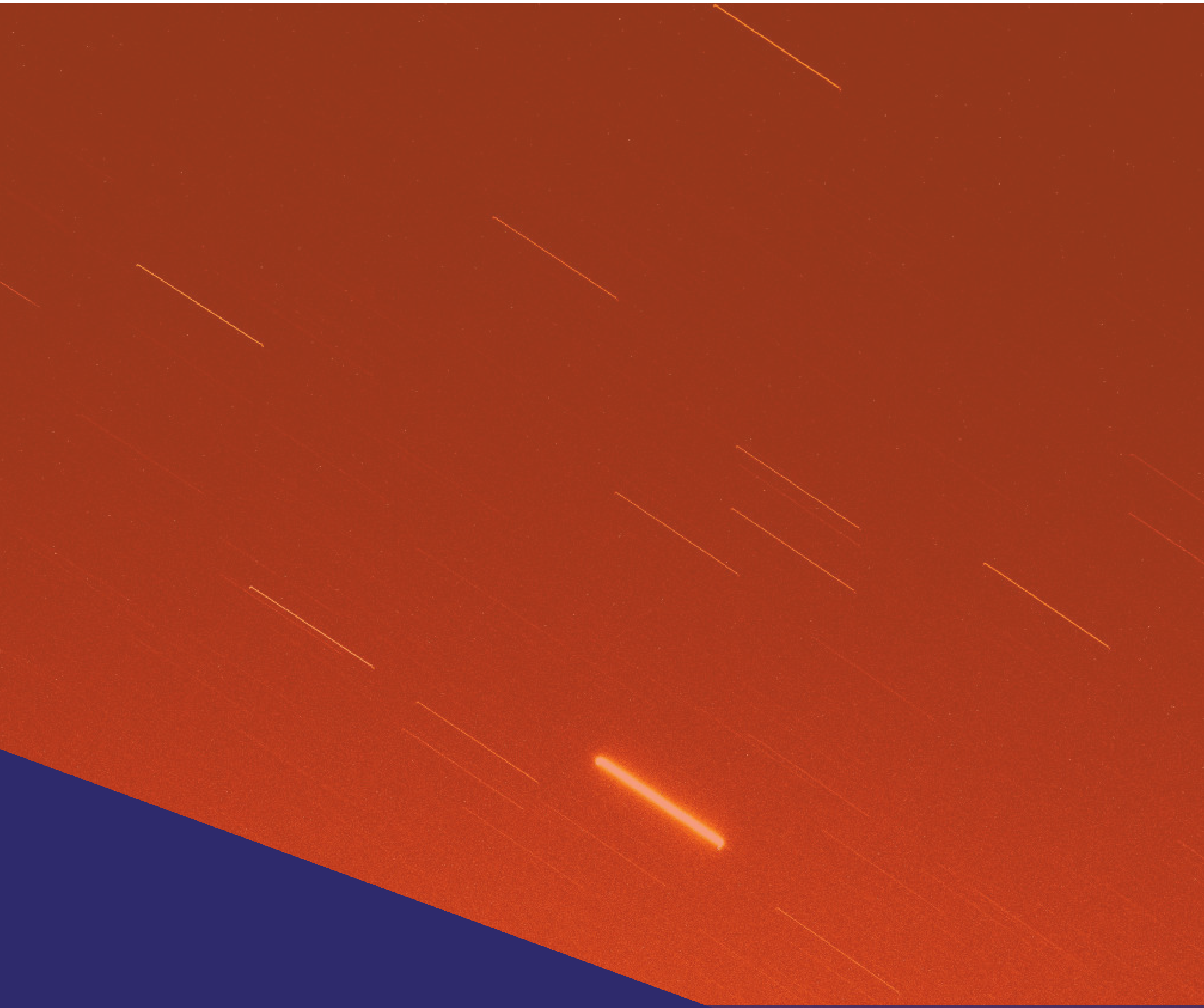
Source: Ibid., 45.

Appendix IV – IPCC Tier Definitions

Tier	Definition	Information Needed	Advantages	Limitations
1	Uses readily available default emissions factors multiplied by sufficiently approximate activity data	• Default emissions factors • Amount of steel, associated materials, and fuel used and produced	• Default emissions factors are readily available for different materials and steel making processes • Limited data collection effort	• Default emissions factors lead to high degrees of scientific uncertainty
2	An intermediate level of complexity found using calculations with site specific emissions factors and carbon contents. Recommends a carbon balance approach for processes in particular	• Site specific emissions factors and carbon content factors • Data on input and output types and quantities	• Higher degree of scientific certainty than Tier 1 with lower measurement efforts than in Tier 3	• More extensive and time consuming than Tier 1 or hybrid
Hybrid (Tier 1/2)	Carbon balance approach with the use of default carbon contents for process emissions	• Default carbon content • Activity Data	• Mass carbon balance approach for processes leads to more accurate reporting	• Similar to Tier 1, default values lead to reporting with higher levels of scientific uncertainty
3	Most specific data required, using a site monitoring system such as a Continuous Emissions Monitoring System (CEMS)	• Site-specific monitoring system that tracks real time data	• Mass carbon balance approach for processes leads to more accurate reporting	• Expensive • Only large steel manufacturers have installed install a CEMS

Source: Prepared by the authors based on IPCC guidelines.

COMET
Coalition On
Materials Emissions
Transparency



The Coalition on Materials Emissions Transparency (COMET) is an initiative between the Columbia Center on Sustainable Investment (CCSI), the Payne Institute for Public Policy at the Colorado School of Mines, and RMI.

Design: Michael Morgan

COMET accelerates supply chain decarbonization by enabling producers, consumer-facing companies, investors, and policy makers to better account for greenhouse gas (GHG) emissions throughout materials supply chains, in harmony with existing GHG accounting and disclosure methods and platforms.

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