Manufacturing and Industrial Processes sector: Aluminium Production Emissions

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1. Introduction

Aluminium is the third most abundant element in Earth's crust right after oxygen and silicon. However, its very reactive nature makes it challenging to exploit. Aluminium has several interesting physical properties that motivate its production: small density, large conductivity, natural resistance to corrosion and ease to shape. It was only in the late 19th century that humankind managed to extract aluminium from ores. Aluminium production in industrial quantities through electrolysis became possible thanks to the large-scale deployment of power generation units. It is currently the second most produced metal in the world, right after steel, with a primary production volume of 70 million metric tonnes in 2023 according to the International Aluminum Institute (IAI, 2024a). It is widely used in many sectors such as construction, packaging, consumer goods, transportation and electricity. Another remarkable property of aluminium is that it can be recycled several times with few degradations, while requiring only 5% of the amount of energy necessary to produce virgin aluminium for each cycle. Around one third of the global aluminium production originated from this secondary production (IAI, 2024b).

Global aluminium production is responsible for 2% of global human-caused greenhouse gas emissions when indirect emissions from electricity are accounted for (GEI, 2022). On top of carbon dioxide (CO_2) emissions, aluminium is also responsible for the production of carbon tetrafluoride (CF_4) and hexafluoroethane (C_2F_6), making it the largest producer of perfluorocarbons (PFCs) globally (Worton et al., 2007).

Aluminium production can be used as a proxy for emissions. By estimating facility-level production, we are therefore able to estimate changes in emissions and guide climate policy. As with any such globally traded commodity, aluminium production is characterised by fierce competition amongst producers. Consequently, facility-level data is rarely made publicly available. In most cases it is only possible to obtain aluminium production at the country/regional level (IAI, 2024a; NBSC, 2024; USGS, 2024) which is often released with substantial delays (~months/years). EU and U.S. plant-level emissions data can be sourced from respective registers (E-PRTR contributors, 2024; US EPA contributors, 2024)

At Climate TRACE, we address the challenges of the temporal and spatial limitations and estimate emissions at individual aluminium facilities with a lower latency.

2. Materials and Methods

An overview of the aluminium making process and the scope of our emissions estimates is provided in Figure 1. A description of how we estimate emissions for different processes is provided in the sections below.

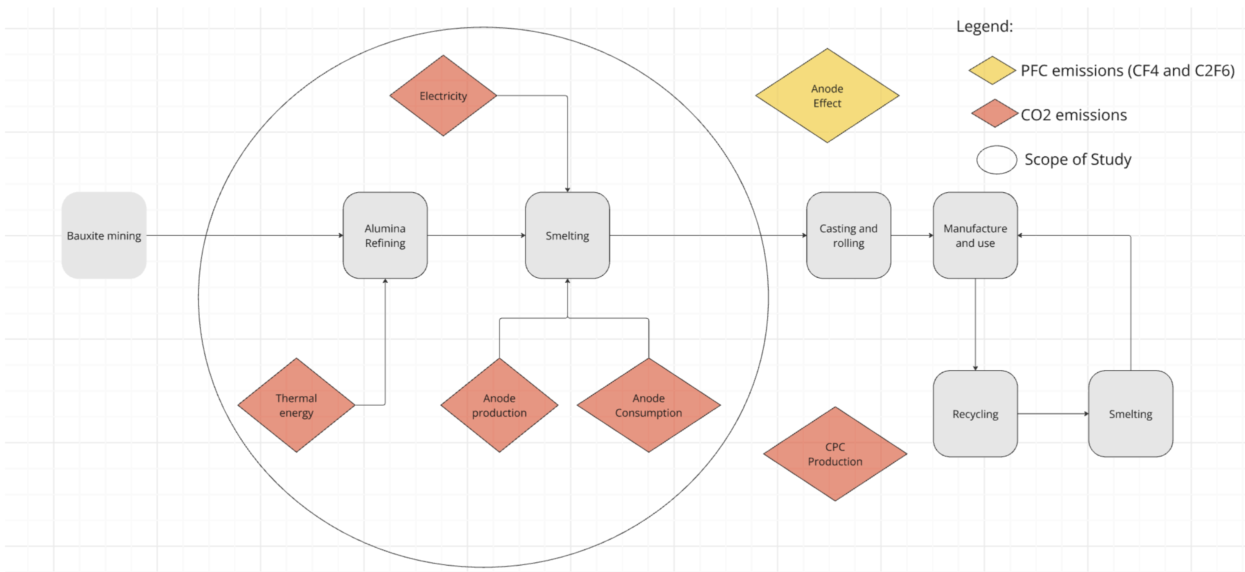

Figure 1 Simplified overview of the aluminium sector describing processes and sources of GHG emissions. The scope of this study focuses on primary aluminium production emissions as identified with a circle.

2.1 An overview of aluminium production and emissions

As shown in Figure 1, the first step in the primary aluminium production consists of the extraction of bauxite ore, an oxidised form of aluminium naturally present in the Earth's crust. This bauxite ore is then refined into alumina through the Bayer process. The resulting alumina is smelted into pure aluminium through the Hall-Héroult electrolysis process before being combined with other metals to create interesting alloys and cast into desired shapes. The electrolysis requires a constant consumption of carbon anode, which can be produced on-site or externally.

There are two principal technology routes for primary aluminium production: Pre-bake process and Søderberg process. In the former, a solid carbon anode is pre–baked prior to the electrolysis stage. Whenever the anode is fully consumed, the process is interrupted for the time it takes to remove and replace the anode. In the latter, a carbon paste is continuously feeding the electrolysis process, and self-baking directly inside the cell. In this work, we do not account for the technology type at the source-level. Global production is largely dominated by the more efficient pre-bake process, but around 4% of global production still originates from Søderberg plants.

Aluminium is also produced through recycling of scraps which can be smelted back into high-purity aluminium. Note that in this work we only focus on primary production. The global emissions from the secondary route accounts for less than 2% of the total sector emissions.

2.2 Datasets employed

We relied on available publicly available data sources and inventories to estimate primary aluminium production, including:

- Process and anode production emission factors from (Ecofys, 2009)
- Primary aluminium production, primary aluminium smelting power consumption, alumina production, metallurgical alumina energy intensity and metallurgical alumina fuel consumption aggregated by regions from the International Aluminum Institute statistics (IAI, 2024a).
- Power grid intensities from Ember's monthly electricity data (Ember, 2024)
- Fuel emissions factors from the Energy Information Administration (EIA, 2021)
- Aluminium asset database from Light Metal Age (R. P. Pawlek, 2024)

2.3 Emissions Scope

Greenhouse gas emissions from primary production of aluminium originate from several manufacturing steps and are detailed in Huglen and Kvande (2016). For aluminium emissions were estimated for the following:

- Direct CO_2 emissions originating from the anode production and consumption during electrolysis.
- Indirect CO_2 emissions associated with the carbon intensity of the local grid for the electrolytic smelting process.
- Emissions originating from the combustion of fossil fuels necessary to elevate the temperature and achieve the Bayer process, an industrial process required to produce alumina.

Other sources of emissions such as anode rodding, casting and bauxite mining were not included but usually account for less than 2% of total emissions. Bauxite mining emissions are reported in a separate Climate TRACE sector. We systematically infer emissions by multiplying the production by relevant emissions factors using the procedure detailed below.

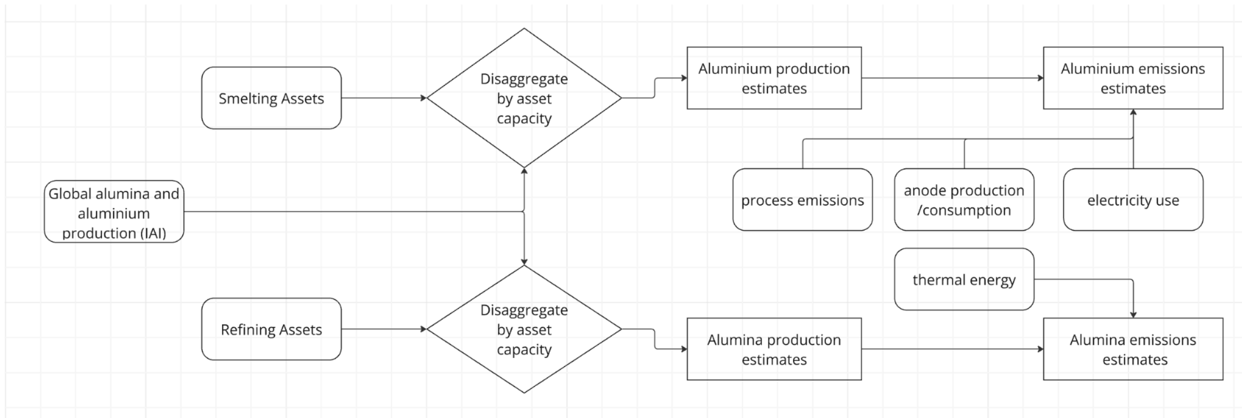

Figure 2 Flowchart of the methodology to calculate facility level emissions for the aluminium smelters and alumina refineries.

2.3.1 Electrolysis process emissions

We use a global emission factor of 2.025 tonnes of CO_2 per tonne of aluminium (t-CO2/t-Al) (Ecofys, 2009) to account for the direct CO_2 emissions for the electrolysis process.

2.3.2 Anode production

We apply a global emission factor of 0.447 t-CO_2/t-Al to account for prebaked anode production, following a benchmark for the EU industry presented in (Ecofys, 2009). Note that this step does not exist for Søderberg plants, which are self-baking anode paste fed directly during the smelting process. Even though our asset database does not distinguish plant by technology type (Søderberg or Pre-bake), we justify using the same emission factor in all cases for two main reasons: firstly, Søderberg type plants account for only 4.3% of the global production; secondly, the absence of pre-baking anode in the Søderberg production is compensated by larger process emissions (Huglen and Kvande ((2016)).

2.3.3 Alumina refining thermal energy emissions

We account for emissions due to the combustion of fossil fuels as a source of heat for the Bayer process which converts bauxite into alumina. We used regional energy intensity and fuel mix as reported by IAI (2024a). The latter allows us to know the share of different energy sources used to produce alumina in different regions. The corresponding fuel emission factors were retrieved from (EIA, 2021).

2.3.4 Indirect emissions

Despite being indirect, emissions originating from power generation to supply the electrolysis process are by far the largest among total emissions, unless very low-carbon electricity, for instance hydropower, is used. To estimate indirect emissions, we multiply the regional electricity use for smelting (IAI, 2024a) with the local grid intensity (Ember, 2024)

2.3 Generating emissions estimates

Emissions estimates begin by extracting monthly alumina and aluminium production data from IAI (2024a). To estimate the production at the facility level, a disaggregation method was applied: for each facility, we computed its share of regional capacity to derive the facility's contribution to the regional production for the given timeframe. An illustrative example of a country with two plants A and B (of capacities C_A and C_B respectively) and a total production P_m for a region in a given month m, the production estimates for these two plants are respectively $P_{A,m}$ and $P_{B,m}$:

- $P_{A,m} = \frac{C_A}{C_A + C_B} \times P_m$
- $P_{B,m} = \frac{C_B}{C_A + C_B} \times P_m$

With the production estimates generated for each aluminium facility, the emission estimates were derived by multiplying the production with the relevant emission factors.

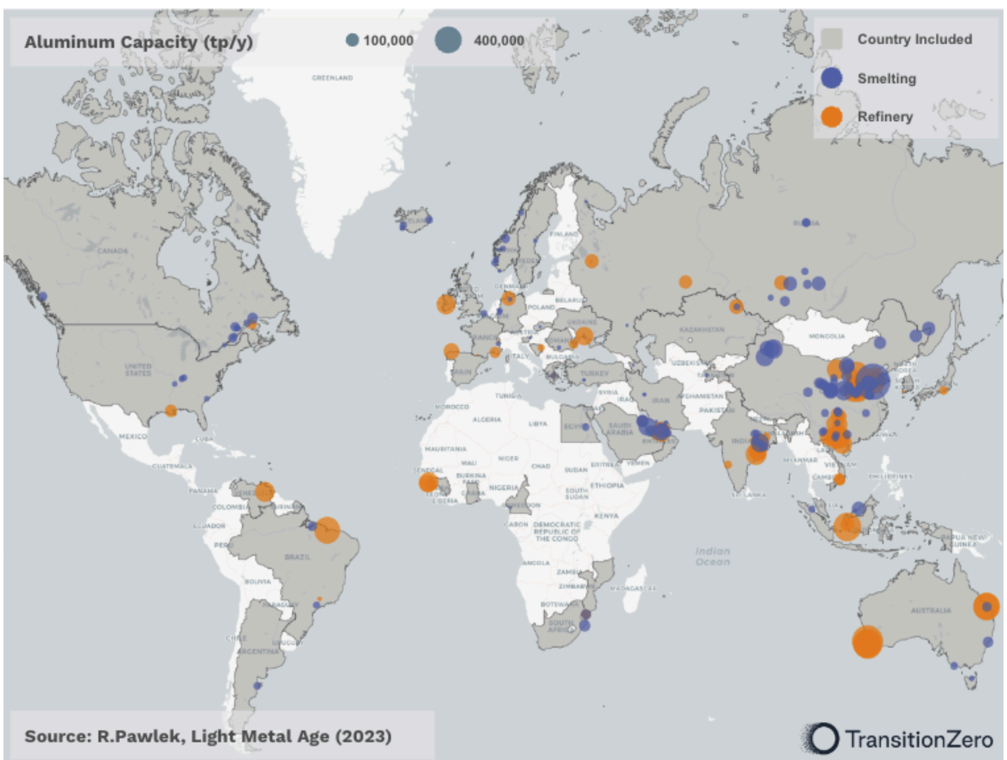

Figure 3 Visual representation of the primary aluminium assets used in this work for 2023. Contributing countries are represented in grey. Refinery assets are represented by orange circles, whilst smelting assets are represented by blue circles. The circle size reflects the plant capacity.

2.4. Coverage and emissions covered

Based on 2023 data, asset level emissions estimates for refineries and smelters accounted for around 70% of the sectors' direct emissions (~400 $MtCO_2$). Most of the shortfall comes from a low (~50%) coverage for refineries.

3. Results

Tables 1 and 2 show the largest emitters in the aluminium sector at country and plant level, respectively. China accounts for around 60% of the global primary aluminium production and alumina production and has some of the biggest smelting facilities.

Table 1 Top 10 emitting countries for primary aluminium production (smelting) in 2023

country	direct emissions ($MtCO_2$)	indirect emissions ($MtCO_2$)	total emissions ($MtCO_2$)
China	104	347	451
India	7.2	29.7	36.9
Russia	9.5	25.5	35
UAE	6.1	18.4	24.5
Australia	3.9	15.1	19
Canada	7.3	7.5	14.8
Bahrain	3.6	10.9	14.5
Saudi Arabia	3.5	10.5	14
South Africa	1.7	6.9	8.6
USA	2.5	5.8	8.3

Table 2 Top 10 emitting aluminium smelters in 2023

plant name	country	capacity (Mt)	total emissions ($MtCO_2$)
Zouping, Shandong	China	6.4	63.3
Fukang, Xinjiang	China	1.9	18.8
Tongshuan	China	1.9	18.8
Xinjiang	China	1.7	17
Jharsuguda	India	1.7	16.7
Askar	Bahrain	1.6	14.5
Taweelah Abu Dhabi	UAE	1.6	14.3
Gansu Dongxing Jiujia	China	1.4	13.4
Baotou Shi	China	1.4	13.4
Chiping Shandong	China	1	13.4

Majority of smelting emissions are linked to electricity consumption. The share of indirect emissions varies by region, depending on grid intensity—80% in India, 77% in China, and 50% in Canada. In contrast, refineries primarily generate emissions from fossil fuel use to produce heat (Table 3).

Table 3 Top 10 emitting countries for primary aluminium production (refinery) in 2023

country	direct emissions ($MtCO_2$)	indirect emissions ($MtCO_2$)	total emissions ($MtCO_2$)
China	137	10.9	147.9
Australia	32.6	2.4	35
Brazil	12.8	0.1	12.9
India	10.8	0.5	11.3
Venezuela	7.1	0.2	7.3
Indonesia	6.3	0.2	6.5
Guinea	5.1	0.2	5.3
Russia	3	0.1	3.1
UAE	2.4	0.1	2.5
Ireland	1.9	0.03	1.9

4. Discussion and conclusions

In this work, we estimate asset level emissions for both alumina refineries and aluminium smelters. Our methodology used asset capacities to allocate a proportional share of the reported national production. The production figures were then multiplied by the most relevant sets of emission factors, covering both direct and indirect emissions of CO_2. The sources of emissions include anode consumption and production, electricity consumption for electrolysis and fuel consumption for alumina production. This is exhaustive enough to cover more than 90% of the greenhouse gas emissions associated with primary aluminium production .

The accuracy of our method is impacted by the several assumptions such as assuming the production of a given asset is relative to that of national production. It is understood that this may not be valid for cases where an asset is offline for long periods of the year. Emissions estimates could be improved by utilising more granular aluminium data - for instance using province-level production data for China. Nevertheless, this work serves as a strong foundational work for the estimation of CO_2 emissions in the aluminium industry which may be utilised to develop more detailed estimates in the future.

5. Supplementary metadata section

Aluminium sector CO_2 emissions are reported for individual assets from January 2021. The emissions described here represent a subset of country-level emissions estimates from the Climate TRACE manufacturing sector. All data is freely available on the Climate TRACE website (https://climatetrace.org/). A detailed description of what is available is described in Tables 4 - 6.

Table 4 Details on the asset metadata**.**

General Description	Definition
Sector definition	*Emissions from aluminium production*
UNFCCC sector equivalent	*2.C.3. Aluminium production*
Temporal Coverage	*2021 – present*
Temporal Resolution	*Monthly*
Data format	*CSV*
Coordinate Reference System	*None. ISO3 country code provided*
Number of emitters available for download	*148 assets across 36 countries*
What emission factors were used?	*Region and process specific emission factors*
What is the difference between a “0” versus “NULL/none/nan” data field?	*“0” values are for true non-existent emissions. If we know that the sector has emissions for that specific gas, but the gas was not modelled, this is represented by “NULL/none/nan”*
total_CO2e_100yrGWPand total_CO2e_20yrGWP conversions	*Climate TRACE uses IPCC AR6 CO_2e GWPs. CO_2e conversion guidelines are here:* *https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport_small.pdf*

Table 5 Definition of the fields in asset dataset.

Data attribute	Definition
sector	manufacturing
source_sub-sector_name	aluminium
source definition	emissions from alumina and aluminium production
start_date	start date for time period of emissions estimation (YYYY-MM-DD format)
end_date	end date for time period of emissions estimation (YYYY-MM-DD format)
asset_identifier	internal identifier
asset_name	name of the facility
iso3_country	ISO 3166-1 alpha-3 country code

Data attribute	Definition
location	well-known text (WKT) point location
type	manufacturing method
capacity	monthly plant capacity
capacity_factor	utilisation rate of refinery/smelters
activity	production estimates
CO2_emissions_factor	direct emissions factor (t-CO2/t-alumina or aluminium)
CH4_emissions_factor	not used; N/A
N2O_emissions_factor	not used; N/A
CO2_emissions	direct emissions estimates (t-CO2)
CH4_emissions	not used; N/A
N2O_emissions	not used; N/A
total_CO2e_100yrGWP	100 years global warming potential (t-CO_2e)
total_CO2e_20yrGWP	20 years global warming potential (t-CO_2e)
other1	direct and indirect emissions factor: includes electricity use (t-CO_2/t-alumina or aluminium)
other2	direct and indirect emissions: includes electricity use (t-CO_2)
other3	electricity use factor (MWh/t-alumina or aluminium)
other4	electricity consumption (MWh)
other5	grid emissions intensity (t-CO2/MWh)
other6	model methodology (e.g. satellite_monitored or extrapolation)
other7	grid marginal operating emissions intensity (t-CO_2/MWh)
model_number	version of the model (e.g. 1, 2, …)

Table 6 Definition for confidence and uncertainty in asset data.

Data attribute	Confidence Definition	Uncertainty Definition
type	● *Very low:* Based on highly speculative or obsolete information. Very low level of confidence in the accuracy of asset classification. ● *Low:* Limited or somewhat outdated data. Low level of confidence in the classification's correctness.	Not used; N/A

Data attribute	Confidence Definition	Uncertainty Definition
	• *Medium:* A mix of historical and more recent data. A medium level of confidence in its accuracy. • *High:* Grounded in comprehensive and recent data. A high level of confidence in the precise classification of the asset. • *Very high:* Extensive, up-to-date, and verified data. A very high level of confidence in the accurate and detailed identification of the asset.	
capacity	• *Very low:* Limited or outdated data, and significant uncertainties exist. • *Low:* Outdated and/or incomplete data. • *Medium:* A mix of historical and recent data. • *High:* Comprehensive and recent data updates. High level of certainty. • *Very high:* Extensive, up-to-date, and verified data. A very high level of certainty.	Not used; N/A
capacity_factor	• *Very low:* Data is sparse or highly unreliable. Considerable uncertainty in capacity factor estimations. • *Low:* Moderate uncertainty in capacity factor calculations. • *Medium:* Data is sufficiently available, though not comprehensive. No absolute accuracy in capacity factor estimations. • *High:* High confidence in the accuracy of capacity factor calculations. • *Very high:* Derived from thorough and validated data sources. Very high precision of capacity factor estimations.	Not used; N/A
activity	• *Very low:* Largely speculative or based on outdated information. A very low level of confidence in activity assessments. • *Low:* Limited or somewhat outdated sources. A low level of confidence in the activity assessments. • *Medium:* A mix of historical and more recent data. Medium level of confidence in activity insights. • *High:* Detailed and current operational data ensures a high level of confidence in the accuracy of activity assessments. • *Very high:* Extensive, verified, and up-to-date data. A very high level of confidence in their accuracy.	±10% of production estimates (based on IPCC)
CO2_emissions_factor	• *Very low:* Highly uncertain due to insufficient or unreliable data. • *Low:* Estimated from incomplete data. Low confidence level in its precision. • *Medium:* A mix of historical and more recent data. Medium level of confidence in their accuracy. • *High:* Derived from comprehensive and recent data. A high level of confidence in their precision.	±10% of assumed value (based on IPCC)

Data attribute	Confidence Definition	Uncertainty Definition
	● *Very high:* Based on extensive and validated data, providing a very high level of confidence in their precision.	
CH4_emissions_factor	Not used; N/A	Not used; N/A
N2O_emissions_factor	Not used; N/A	Not used; N/A
CO2_emissions	● *Very low:* Based on very rough estimations or outdated information. A very low level of confidence in its accuracy. ● *Low:* Estimated from incomplete data. Low confidence level in its precision. ● *Medium:* A mix of historical and more recent data. Medium level of confidence in their accuracy. ● *High:* Derived from comprehensive and recent data. A high level of confidence in their precision. ● *Very high:* Based on extensive and validated data, providing a very high level of confidence in their precision.	±20% of emissions estimates
CH4_emissions	Not used; N/A	Not used; N/A
N2O_emissions	Not used; N/A	Not used; N/A
total_CO2e_100yrGWP	● *Very low:* Based on very rough estimations or outdated information. A very low level of confidence in its accuracy. ● *Low:* Estimated from incomplete data. Low confidence level in its precision. ● *Medium:* A mix of historical and more recent data. Medium level of confidence in their accuracy. ● *High:* Derived from comprehensive and recent data. A high level of confidence in their precision. ● *Very high:* Based on extensive and validated data, providing a very high level of confidence in their precision.	±20% of emissions estimates
total_CO2e_20yrGWP	● *Very low:* Based on very rough estimations or outdated information. A very low level of confidence in its accuracy. ● *Low:* Estimated from incomplete data. Low confidence level in its precision. ● *Medium:* A mix of historical and more recent data. Medium level of confidence in their accuracy. ● *High:* Derived from comprehensive and recent data. A high level of confidence in their precision.	±20% of emissions estimates

Data attribute	Confidence Definition	Uncertainty Definition
	• *Very high:* Based on extensive and validated data, providing a very high level of confidence in their precision.	

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Disclaimer: The emissions provided for this sector are our current best estimates of emissions, and we are committed to continually increasing the accuracy of the models on all levels. Please review our terms of use and the sector-specific methodology documentation before using the data. If you identify an error or would like to participate in our data validation process, please contact us.

6. References

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