Manufacturing sector:
Aluminum Manufacturing Emissions

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1. Introduction

Aluminum 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. Aluminum 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 aluminum from ores. Aluminum 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 69 million metric tonnes in 2022 according to the International Aluminum Institute (IAI, 2023a). Thus, it is widely used in many sectors such as construction, packaging, consumer goods, transportation and electricity. Another remarkable property of aluminum is that it can be recycled several times with few degradations, while requiring only 5% of the amount of energy necessary to produce virgin aluminum for each cycle. Around one third of the global aluminum production originated from this secondary production (IAI, 2023b).

Global aluminum 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, aluminum 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).

Aluminum production can be used as a proxy for emissions (using emission factors expressed in kg CO_2/ tonne of aluminum) and therefore it is desirable to ascertain real time and in-depth production values to guide future climate policy. With any such globally traded commodity however, it is characterized by fierce competition amongst producers and, as a consequence, facility level production data is rarely made publicly available. In most cases it is only possible to obtain aluminum production/emissions quantities at the country or regional level, reported at different scopes, and often with a substantial delay (~years) in obtaining the data (E-PRTR contributors, 2022; UNFCCC contributors, 2022; US EPA contributors, 2022).

In this work we look to address both the temporal and spatial limitations in traditional reporting of aluminum production/emissions to provide more timely, accurate and comparable facility level data.

2. Materials and Methods

The goal of this work is to estimate emissions for the primary aluminum sector at the asset-level on a monthly basis from 2015 to 2022. Here, we present a brief review of the aluminum making process and use it to specify the scopes of our estimated emissions (Figure 1). Additionally, datasets employed in this work are listed, followed by how national, regional or global emission factors were extracted and how asset-level production was estimated.

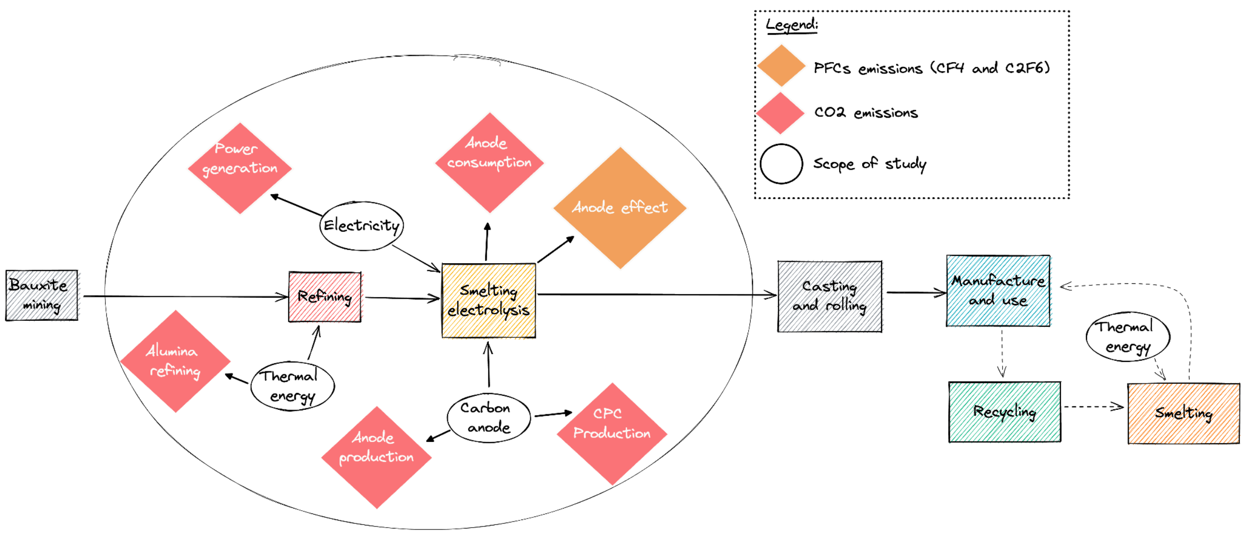

Figure 1 Simplified overview of the aluminum sector describing processes and sources of GHG emissions. The scope of this study focuses on primary aluminum production emissions, identified by the circles in the figure. A description of how we estimate each emissions source is provided in the sections below.

2.1 An overview of aluminum production and emissions

As shown in Figure 1, the first step in the primary aluminum production consists of the extraction of bauxite ore, an oxidized form of aluminum 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 aluminum through the Hall-Héroult electrolysis process before being combined with other metals to create interesting alloys and being casted in 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 aluminum 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 on 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.

Aluminum is also produced through recycling of scraps which can be smelted back into high-purity aluminum. Around a third (35%) of global aluminum production comes from the secondary route (IAI, 2023b). Note that in this work we only focus on primary production, in the scope delimited by the big circle of Figure 1. 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 aluminum production, including:

- CF_4 and C_2F_6 emission factors for aluminum production from (Marks and Nunez, 2018)
- Process and anode production emission factors from (Ecofys, 2009)
- Global Warming Potential for PFCs from the Intergovernmental Panel on Climate Change (IPCC, 2021).
- Primary aluminum production, alumina production, primary aluminum smelting energy intensity, primary aluminum smelting power consumption, metallurgical alumina energy intensity, metallurgical alumina fuel consumption aggregated by regions from the International Aluminum Institute statistics (IAI, 2023a).
- Yearly aluminum and alumina production by country for those reported by the British Geological Survey (BGS, 2022).
- Country-level CO_2, CF_4 and C_2F_6 emissions reported by the United Nations Framework on Climate Change (UNFCCC contributors, 2022).
- Share of Pre-bake and Søderberg cell types by regions from the International Aluminum Institute (IAI, 2022b)
- Power grid intensities from the International Energy Agency (IEA, 2019; Ember, 2020)
- Fuel emissions factors from the Energy Information Administration (EIA, 2021)
- Alumina Refining asset database from Industrial Info Resources (IIR) (IIR, 2023)
- Aluminum asset database from Light Metal Age (R. Pawlek, 2023)

All of the above datasets were combined to provide detailed information for each identified aluminum facility to estimate emissions.

2.2 Model and emission factors

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

- Direct CO_2 emissions originating from the anode production and consumption during electrolysis as well as direct PFCs emissions.
- Indirect CO_2 emissions associated:
    - carbon intensity of the electricity supplying the electrolysis process, emissions occurring during the anode production
    - calcined petroleum coke production.
- 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 (aluminum oxide) .

Other sources of emissions such as anode rodding, casting and bauxite mining, the primary ore that contains aluminum, were not included but usually account for less than 2% of total emissions (Huglen and Kvande, 2016). The emissions associated with bauxite mining are reported in a separate Climate TRACE sector. We systematically infer emissions by multiplying the production by several emissions factors using the procedure detailed below.

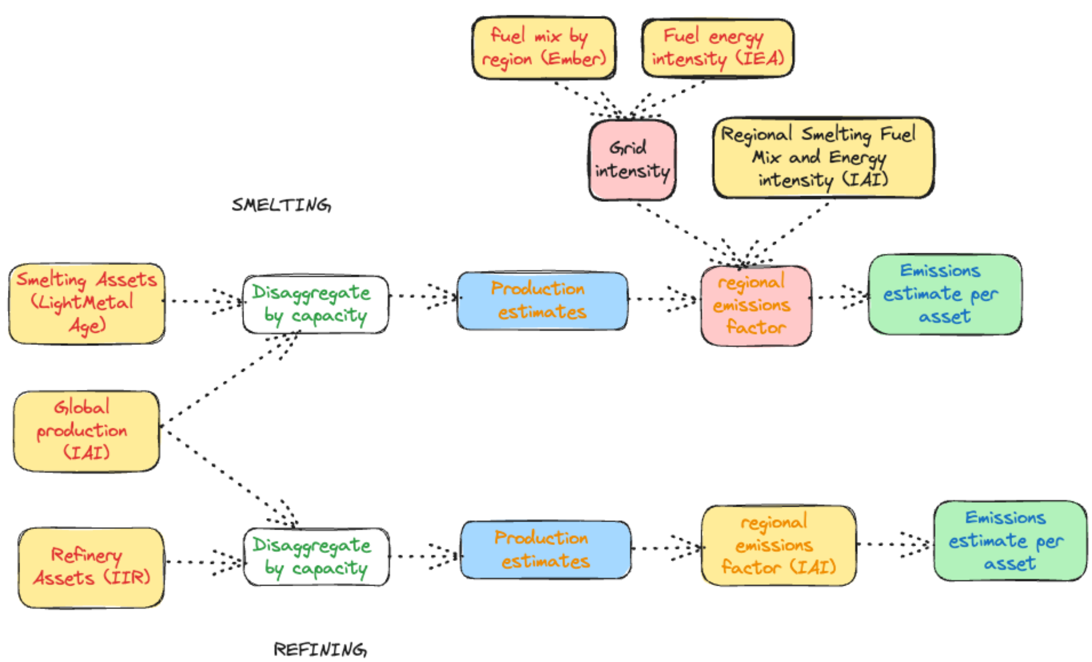

Figure 2 Flowchart of the methodology to calculate source level emissions for the aluminum smelters and alumina refineries.

2.2.1 Electrolysis process emissions

We use a global emission factor of 2.025 tCO_2 per tonne of aluminum (Ecofys, 2009) to account for the direct CO_2 emissions for the electrolysis process. More details can be found in Annex 1.

2.2.2 Indirect electricity 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. In order to estimate indirect emissions, we start by expressing each source of electricity from the regional primary aluminum smelting power consumption reported by the IAI as a percentage of the total of all sources. Then, we multiply this outcome by primary aluminum smelting energy intensity reported by the IAI, and then by the carbon intensity of each source of electricity. The final emission factor was obtained summing each electricity source. A detailed example showing all the intermediate calculation steps is shown in Annex 2. We obtained yearly emission factors at the country-level, used regional data for the power consumption and energy intensity data and country-level data from the IEA for the carbon intensity of coal, natural gas and oil.

2.2.3 Anode production

We apply a global emission factor of 0.447 tCO_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 directly during the smelting process. Even though our asset database does not distinguish plant by technology type (Søderberg or Pre-bake), we justify using this emission factor in all cases by two main reasons: first, the production from Søderberg plants is monitory, accounting for only 4.3% of the production worldwide in 2021 (IAI, 2022a); second, the absence of that step in the Søderberg production is compensated by larger process emissions as can be seen from Huglen and Kvande (2016).

2.2.4 Alumina refining thermal energy emissions

We accounted 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 metallurgical alumina energy intensity and metallurgical alumina fuel consumption reported by regions by the IAI. The latter allows us to know the fraction of each energy source to produce 1 tonne of alumina for each region. We multiplied these fractions by the energy intensity and the corresponding fuel emission factors, using the following values retrieved from (EIA, 2021). For electricity, we assumed the refining plants were being supplied by their national grid, and therefore used the grid intensities derived from IEA, 2019 and Ember, 2020. The final emission factor was obtained by adding the contributions of all the fuel sources, expressed in tCO_2/ t-Al_2O_3.

A summary of all emission factors with typical values from two selected countries is available in Annex 3.

2.3 Estimation of the emissions

We start by extracting monthly aluminum production data from IAI. In order to estimate the production on the asset-level, a disaggregation method was applied: for each facility, we computed its share of regional capacity to derive the facility's contribution 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 and a given month m, the 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 aluminum facility, the emission estimates were derived by multiplying the production by the relevant emission factors.

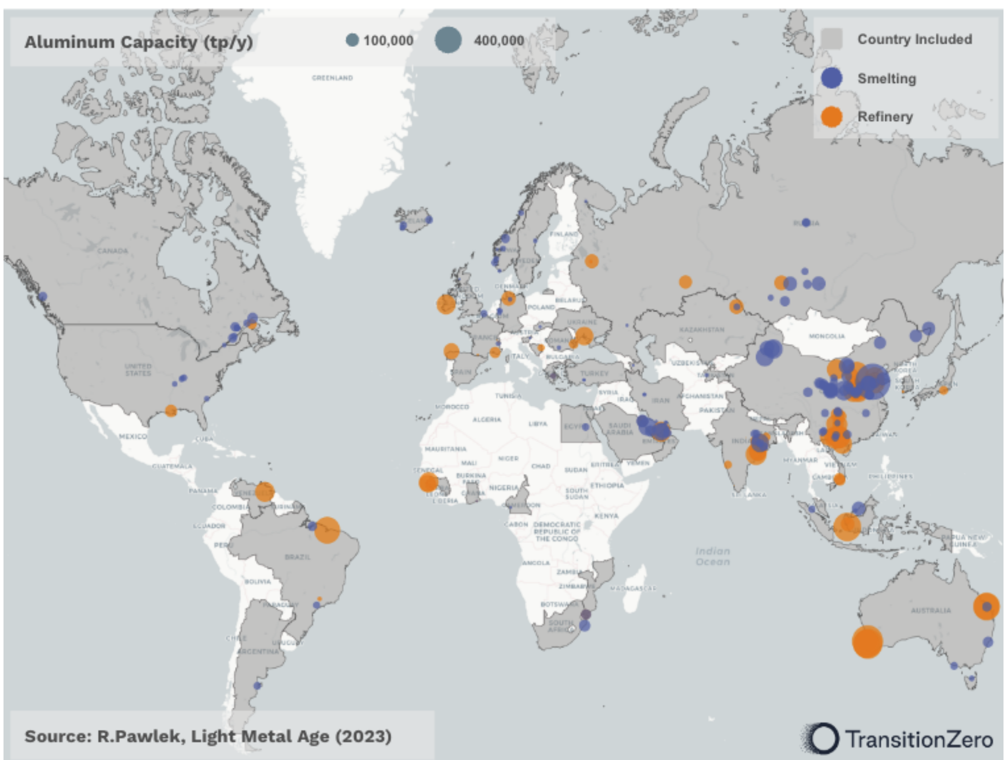

Figure 3 Visual representation of the primary aluminum database used in this work. Contributing countries are represented in gray, refinery assets are represented by orange circles, whilst smelting assets are represented by blue circles. The circle size reflects the refinery or smelting capacity. This visual shows the status of global capacities in 2023.

2.4. Coverage and emissions covered

The asset database contains 161 operational smelters accounting for 76.4 Mt of aluminum/year of installed capacity across 43 countries, which accounts for around 97% of total primary aluminum production (based on 2022 values). To generate country-level emissions, each asset in a country was summed to the total. An overview of the coverage can be found in Figure 3.

3. Results

Table 1 and 2 shows the biggest producers and emitters in the aluminum sector at country and plant level, respectively. China accounts for around 60% of the global primary aluminum production. Majority of the alumina refineries are also located in China

Table 1 Top producers and emitters in the aluminum sector (smelting) - by country

Country	Facility	CO_2 Emissions ($MtCO_2$)	Production (Mt)
China	Smelting	100	40.4
India	Smelting	7	2.8
Canada	Smelting	6.9	2.8
Russia	Smelting	6.3	2.5
Abu Dhabi	Smelting	5.9	2.4
Australia	Smelting	3.8	1.5
Bahrain	Smelting	3.5	1.4
Saudi Arabia	Smelting	3.4	1.4
Germany	Smelting	3.3	1.3
France	Smelting	2.6	1

Table 2 Top producers and emitters in the aluminum sector (smelting) - by plant

Plant name	Facility	Country	CO_2 emissions ($MtCO_2$)	Production (Mt)	Capacity (Mt)
Zouping	Smelting	China	14	5.7	6.4
Fukang	Smelting	China	4.2	1.7	1.9
Tongshuan	Smelting	China	4.2	1.7	1.9
Xinjiang	Smelting	China	3.8	1.5	1.7
Askar	Smelting	Bahrain	3.5	1.4	1.6
Taweelah	Smelting	Abu Dhabi	3.4	1.4	1.6
Jharsuguda	Smelting	India	3.2	1.3	1.7
Gansu	Smelting	China	3	1.2	1.4
Baotou	Smelting	China	3	1.2	1.4
Chiping	Smelting	China	2	1	1

Figure 4 highlights the results based on aggregated annually reported emissions for selected plants in the EU and US, respectively (E-PRTR contributors, 2022, US EPA contributors, 2022). Only direct CO_2 emissions are compared. Data from only 9 assets (3 in EU and 6 in US) were available for comparison.

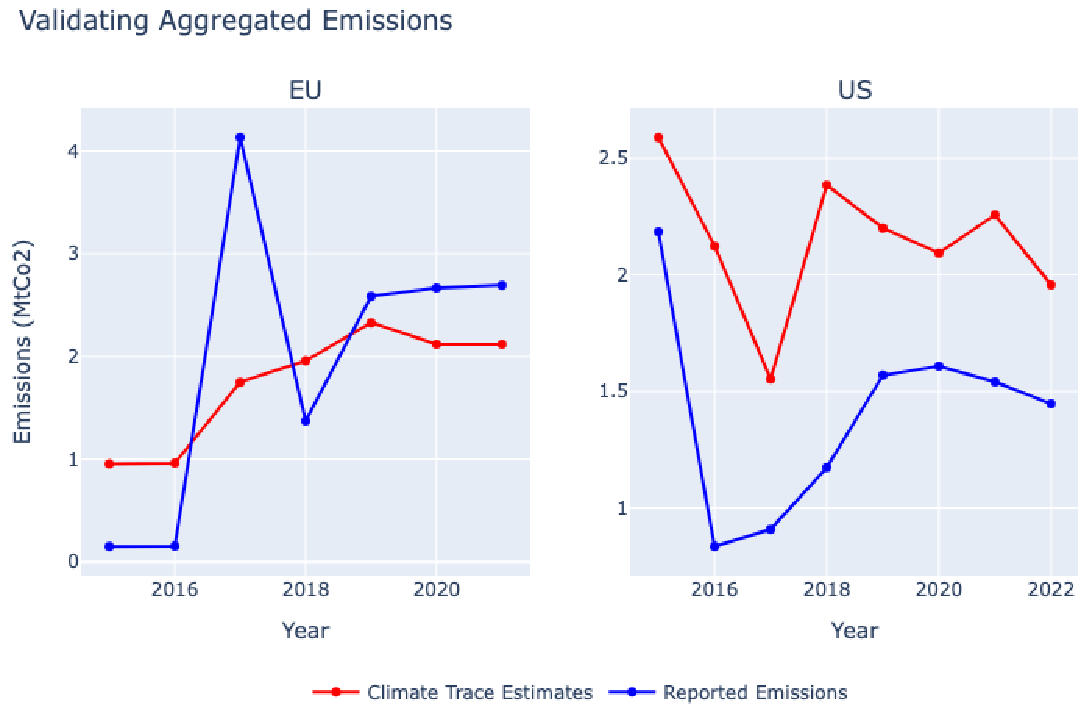

Figure 4 Comparison of reported emissions and Climate TRACE emissions estimates for the EU (left) and US (right).

4. Discussion and conclusions

In this work, a total of 171 operational smelters are analyzed and modeled, which accounts for around 97% of total primary aluminum production (based on 2022 values).

To estimate source level emissions, our methodology takes known asset capacities as a fraction of the national share and uses this information to allocate a proportional share of the national production. The production figures were then multiplied by the most relevant sets of emission factors. The most up-to-date publicly available sources were chosen to estimate emission factors, covering both direct and indirect emissions of CO_2. The sources of emissions include anode consumption and production including emissions from the production of the calcined petroleum coke that is used to produce them, electricity consumption for electrolysis and fuel consumption for alumina production. This is exhaustive enough to cover more than 98% of the greenhouse gas emissions associated with primary aluminum production (Huglen and Kvande, 2016).

The accuracy of our method is impacted by the several assumptions we made about each asset, 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 utilizing more granular aluminum 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 aluminum industry which may be utilized to develop more detailed estimates in the future.

5. Supplementary metadata section

Aluminum sector CO2 emissions are reported for individual assets for the period 2015 - 2022. The emissions described here represent a subset of specific 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 3 and 4.

Table 3 Metadata for Emissions for aluminum sector**.**

General Description	Definition
Sector definition	*Emissions from aluminum production*
UNFCCC sector equivalent	*2.C.3. Aluminum production*
Temporal Coverage	*2015 – 2022*
Temporal Resolution	*Monthly*
Data format	*CSV*
Coordinate Reference System	*None. ISO3 country code provided*
Number of emitters available for download	*161 assets across 43 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 modeled, this is represented by "NULL/none/nan"*
total_CO2e_100yrGWP and 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 4 Aluminum sector description for confidence and uncertainty in emissions.

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. ● *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.	Not used; N/A
capacity_description	● *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. Very high level of certainty.	Not used; N/A
capacity_factor_description	● *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_description	● *Very low:* Largely speculative or based on outdated information. A very low level of confidence in activity assessments.	10% of asset production (based on IPCC)

	• *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.	
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. • *Very high:* Based on extensive and validated data, providing a very high level of confidence in their precision.	10% of asset (based on IPCC)
CH4_emissions_factor	Not used; N/A	Not used; N/A
N2O_emissions_factor	Not used; N/A	Not used; N/A
other_gas_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 asset emissions
CH4_emissions	Not used; N/A	Not used; N/A

N2O_emissions	Not used; N/A	Not used; N/A
other_gas_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 asset emissions
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. ● *Very high:* Based on extensive and validated data, providing a very high level of confidence in their precision.	20% of asset emissions

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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.

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7. Appendices

7.1. List of acronyms

Table 5 List of acronyms

Al	Aluminum
BGS	British Geological Survey
CF_4	Carbon Tetrafluoride
C_2F_6	Hexafluoroethane
CO_2	Carbon dioxide
CPC	Calcined Petroleum Coke
EIA	Energy Information Administration
E-PRTR	European Pollutant Release and Transfer Register
IAI	International Aluminum Institute
IEA	International Energy Agency
IIR	Industrial Info Resources
IPCC	Intergovernmental Panel on Climate Change
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
PFC	Perfluorocarbon
UNFCCC	United Nations Framework Convention on Climate Change
US EPA	United States Environmental Protection Agency

7.2 Annex 1: Physical origin of electrolysis direct emissions

CO2 emissions: Anode consumption

The dominant chemical reaction during the electrolysis process is the following

$$Al_2O_3 \text{ (dissolved)} + 3\,C\text{ (s)} = 4\,Al\text{ (l)} + 3\,CO_2\text{ (g)}$$

PFC emissions: Anode effect
In order to perform the electrolysis, the alumina powder is dissolved into a bath of molten cryolite (Na_3AlF_6), which reduces the process temperature significantly. A physical phenomenon, so-called anode effect, occurs when the concentration of alumina becomes too small, resulting in a lower conductivity of the electrolyte and triggers instability in the form of rapid fluctuations voltage between the anode and the cathode. Higher voltages trigger a reaction that turns the fluorine contained in the cryolite in PFCs according to the two following reactions

$$Na_3AlF_6 + 3/4\,C = Al + 3NaF + 3/4\,CF_4\,(g)$$
$$Na_3AlF_6 + C = Al + 3NaF + 1/2\,C_2F_6\,(g)$$

The aluminum industry made good progress in reducing these undesired emissions which are also associated with a drop of energy, as the reactions require energy and consumes carbon from the anode. However, these emissions must still be accounted for, and significant variations among assets exist depending on the technology type and monitoring tools available to regulate the anode effect.

7.3 Annex 2: Example of calculation steps of the electricity emission factor for France

Table 6 Illustration of the method to extract electricity emission factor for France in 2019.

Primary aluminum smelting energy intensity (total energy) in Europe, in 2019: 15,474 kWh / tonne of aluminum.					
Source	*Total electricity use (GWh)*	*Share of total electricity use*	*Normalized electricity use (kWh / t Al)*	*Carbon intensity of electricity (gCO_2 / kWh)*	*Emission factor (tCO_2 / t Al)*
Coal	6,153	5.28 %	818	932.0	0.762
Natural gas	2,062	1.77 %	274	348.0	0.095
Oil	293	0.25 %	39	695.6	0.027
Hydro	93,055	79.9 %	12,364	23.0	0.284
Nuclear	7,258	6.23 %	964	12.0	0.011
Other Renewable	6,754	5.8 %	897	30.0	0.027
Other non-renewable	883	0.8 %	117	1,567.7	0.183

7.4 Annex 3: Summary of all emission factors: two examples

Below is a summary of all the estimated emissions through two selected countries, using 2022 data: France and China.

Table 7 Summary of all emission factors for France in 2022.

Emission source	Emission type	Inputs	Emission factor (tCO_2/t-Al)
Anode consumption, CO_2	Direct	Global emission factor	2.025
Electrolysis electricity use	Indirect	Regional aluminum power consumption and energy intensity, national electricity emission factors for fossil sources, global emission factors for the others	3.08
Anode production	Direct	Global emission factor	0.447

Table 8 Summary of all emission factors for China in 2022.

Emission source	Emission type	Inputs	Emission factor (tCO_2eq/t-Al)
Anode consumption, CO_2	Direct	Global emission factor	2.025
Electrolysis electricity use	Indirect	Regional aluminum power consumption and energy intensity, national electricity emission factors for fossil sources, global emission factors for the others	10.35
Anode production	Direct	Global emission factor	0.447