Manufacturing sector: Aluminum

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1. Introduction

Aluminum is the third most abundant element in Earth's crust right after oxygen and silicon. However, it's 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 68 million metric tonnes in 2021 according to the International Aluminum Institute (IAI, 2022a). 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. In 2020, one third of the global aluminum production originated from this secondary production (IAI, 2020).

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 (i.e., 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 characterised 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. More specifically, we have aimed to deliver aluminum production and emissions estimates on a monthly basis (with 1 month lag) for all assets identified in the primary aluminum plant database published by Light Metal Age (R. Pawlek, 2022).

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 the end of 2021. Here, we present here a brief review of the aluminum making process and use it to specify the scopes of our estimated emission (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. A list of acronyms is provided in Table 1 in the Supplementary section.

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 has to 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 asset-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. In 2020, a third of global aluminum production came from this secondary route (IAI, 2020). Note that in this work we only focus on primary production, in the scope delimited by the big circle of Figure 1. Given that the emission intensity of aluminum making from the secondary route is at most 0.6 tCO_2eq / t Al (IAI, 2022a), the global emissions from the secondary route accounts for ~ 2% of the total from the aluminum sector.

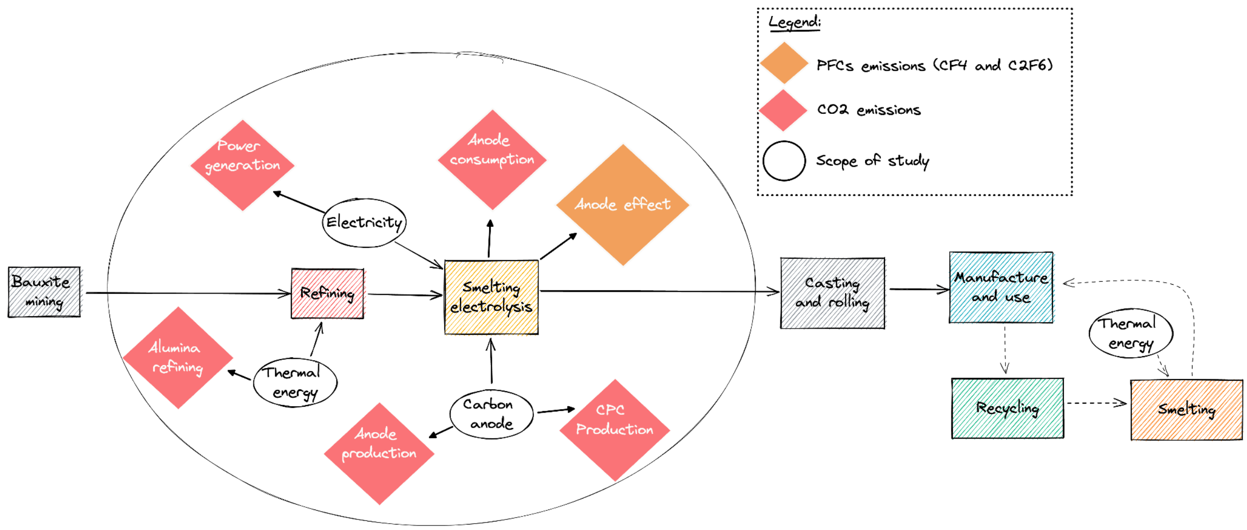

Figure 1 Simplified overview of the aluminum sector describing processes and sources of GHG emissions. The scope of this study focuses on primary aluminum production emissions, identified by the circles in the figure. A description of how we estimate each emissions source is provided in the sections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

2.1 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 (J.A Moya et al., 2015)
- 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, 2022a).
- 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)
- Hydropower electricity emission factor from (Ubierna et al., 2022)
- Nuclear, wind and solar electricity emission factors from (IPCC, 2018a)
- Power grid intensities from the International Energy Agency (IEA, 2020)
- Fuel emissions factors from the Energy Information Administration (EIA, 2021)
- Aluminum asset database from Light Metal Age (R. Pawlek, 2022)

All the datasets above were combined to provide detailed information for each identified asset within their associated country in order to generate emission estimates.

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, we modeled direct CO_2 emissions originating from the anode production and consumption during electrolysis as well as direct PFCs emissions. We also estimated indirect CO_2 emissions associated with the carbon intensity of the electricity supplying the electrolysis process, emissions occurring during the anode production, as well as calcined petroleum coke production. For alumina, a compound that contains aluminum, we estimated 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, the primary ore that contains aluminum, are not included but usually account for less than 2% of total emissions (Huglen and Kvande, 2016). The emissions associated with bauxite mining are reported as a separate Climate TRACE sector.

We systematically infer emissions by multiplying the production by several emissions factors using the procedure detailed below.

2.2.1 Electrolysis process emissions

We use a global emission factor of 1.514 tonnes (t) of CO_2 per tonne of aluminum introduced in J.A Moya et al. (2015) to account for electrolysis process CO_2 emissions. More details about the physical nature of these emissions can be found in Annex 1.

2.2.2 Perfluorocarbon emissions

Perfluorocarbon (PFC) emissions occur during the electrolysis because of the so-called anode effect. More details about the physical mechanism are given in Annex 1.

When possible, we extracted an emission factor for a given country by dividing their yearly emissions of CF_4 and C_2F_6 emissions from the aluminum sector reported in UNFCCC by their corresponding yearly aluminum production reported by BGS. We extrapolated the latest available year to estimate current emissions. This approach was used for 19 countries: Australia, Canada, France, Germany, Greece, Iceland, Kazakhstan, Netherlands, New Zealand, Norway, Romania, Russia, Slovakia, Slovenia, Spain, Sweden, Turkey, USA, and the United Kingdom.

For the other countries we used the emission factors reported in Marks and Nunez (2018). These reported emission factors are intended to update from the IPCC 2008 Guidelines (IPCC, 2006) since they account for the progress of the aluminum industry and account for the previously unspotted continuous low-voltage anode effect. Since the emission factors differ for Pre-bake and Søderberg plant type, we weighted them according to the production ratio between these two technologies within the region in which a given country belongs to, using regional data from the IAI in the 2019 Life Cycle Inventory.

Emission factors expressed in t CF_4/ t Al and t C_2F_6/ t Al are converted into t CO_2eq / t Al by multiplying them with the appropriate global warming potential from (IPCC, 2021).

2.2.3 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 from hydropower, is used. In order to estimate indirect emissions, we start by expressing each source of electricity from the regional primary aluminum smelting power consumptions 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.

2.2.4 Anode production

We apply a global emission factor of 0.324 t CO_2 /t Al to account for prebaked anode production, following a benchmark for the EU industry presented in (J.A Moya et al., 2015). Note that this step does not exist for Søderberg plants, which are self-baking anode paste directly during the aluminum 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).

2.2.5 Calcined petroleum coke production

Calcined petroleum coke (CPC) is the main ingredient for prebaked anode production, and its production gives rise to emissions that are not negligible. We applied a global emission factor of 0.3 t CO_2 /t Al, following the value stated in Huglen and Kvande (2016). Note that since our asset database does not distinguish between technology this implies that we apply this emission factor for Søderberg cell types. This was justified since, in that case, anode paste is also mostly made from CPC.

2.2.6 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). These values are adapted from (IPCC, 2018b). For electricity, we assumed plants were being supplied by their national grid, and therefore used the grid intensities derived from the IEA. The final emission factor was obtained by adding the contributions of all the fuel sources, expressed in t CO_2/ t Al_2O_3.

Assuming 2.07 metric tonnes of alumina are consumed to produce 1 metric tonne of aluminum (derived by dividing the production of alumina and aluminum reported by the IAI between January 2010 and August 2022), we converted the alumina energy emission in t CO_2/ t Al by multiplication with the inferred alumina consumption in the smelters.

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 asset, the emission estimates were derived by multiplying the production by the relevant emission factors.

2.4. Coverage and emissions covered

The asset database contains 148 operational smelters accounting for 76.4 Mt of aluminum/year of installed capacity across 36 countries, which accounts for 97% of total primary aluminum production (based on 2021 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 2.

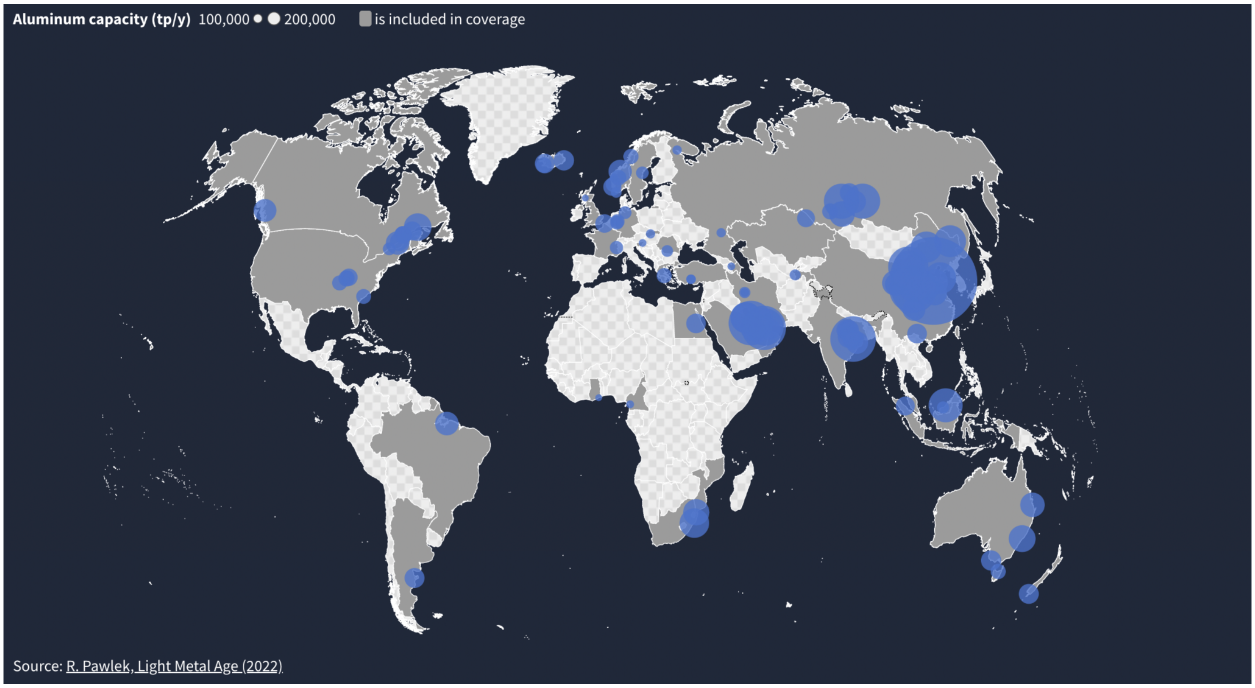

Figure 2 Visual representation of the primary aluminum database used in this work. Contributing countries are represented in gray and assets are represented by blue circles whose area grows with capacity. This visual shows the status of global capacities in 2021.

3. Results

Asset level emissions estimates are the target of this work. However, it is also useful to validate our results at a more aggregated level.

We start by comparing emissions on the global scale. IAI reports global emission intensities for different steps in the production of primary aluminum between 2015 and 2018, as well as production numbers (both regional and world aggregates). We discard the reported emissions intensities from transport, mining and ancillary materials (except the one related to anode production, included in the CPC production category), and classify all the remaining ones into of the five categories shown in Figure 3 in order to produce a fair comparison.

Focusing on 2018, the direct emissions associated with aluminum production (excluding emission from the electrolysis electricity category), the emission estimates generated here are 313 Mt CO_2 in 2018, in-line with IAI's derived numbers of 304 $MtCO_2$ for the same year (3% mean absolute percentage error over the observed period). Our model yields slightly larger emissions for PFC, which might be linked to our use of updated emission factors, including the low-voltage anode effect.

Greater disparity appears when we include electrolysis electricity emissions, where we estimate 805 $MtCO_2$ in 2018 vs. 969 $MtCO_2$ derived from the IAI's numbers (17% mean absolute percentage error over the observed period). Without many details on how IAI electricity emission intensities are calculated, we can only assume the difference can be due to our use of more localised emission intensities for power generation, as opposed to the global number used by IAI to make the comparison. Note that emissions from the electricity-related emissions are already accounted for in the Climate TRACE Electricity generation sector.

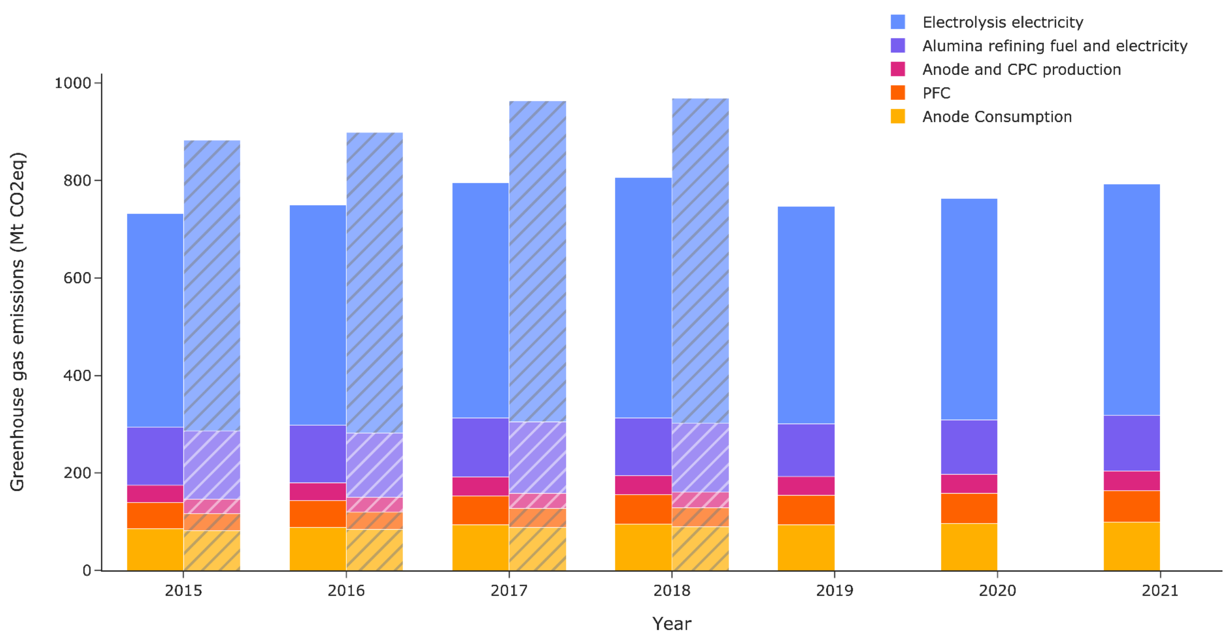

Figure 3 Comparison of global emissions from primary aluminum production, Climate TRACE (no pattern) and IAI (crosshatched). Colors indicate the primary aluminum production process discussed in section 2.

Figure 4 highlights the results based on aggregated annually reported emissions for selected plants (as stated in Section 3.2) in the EU and US, respectively. Only direct CO_2 emissions are compared. In both cases data is compared as aggregate values across years 2015 to 2020 and our own estimates demonstrate good levels of accuracy to reported data for selected years, which we measure using the mean absolute error (MAE) and mean absolute percentage error (MAPE). For the EU a MAE (MAPE) of 0.5 $MtCO_2$/a (26%) and the US a 0.9 $MtCO_2$/a (26%) is achieved. It should be noted that the number of assets compared each year is listed above each marker. In the US for 2016 and 2017 we see a larger disparity between reported emissions and our own estimates. In these cases, the error can likely be attributed to assets which are not producing proportionally with the national average in addition to the low coverage of US assets that were available for validating our results.

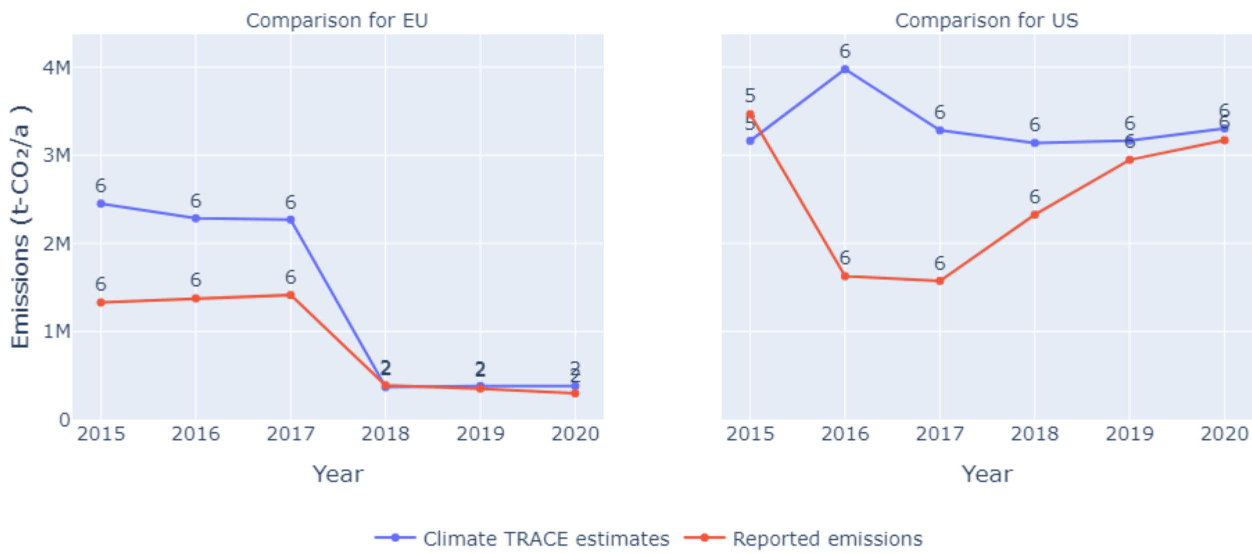

Figure 4 Comparison of reported emissions and Climate TRACE emissions estimates for the EU (left) and US (right). Number of available assets for each comparison shown for each data point.

4. Discussion and conclusions

In this work, a total of 148 operational smelters are analysed and modelled, which accounts for 97% of total primary aluminum production (based on 2021 values).

To estimate emissions at the asset level, our methodology takes known asset capacities as a fraction of the national share and uses this information to allocate a proportional share of the known national production, before multiplying the derived production number by the most relevant sets of emission factors. The most up-to-date publicly available sources were chosen to estimate emission factors with the largest number of details possible, covering both direct and indirect emissions of CO_2, as well as direct emissions of CF_4 and C_2F_6. The sources of emissions include anode consumption and production including emissions from the production of the calcined petroleum coke that makes them, anode effect, 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).

In terms of accuracy, we have measured an aggregated MAE (MAPE) accuracy of 0.5 Mt/a (26%) and the US a 0.9 Mt/a (26%) for the EU and US respectively on facilities available for analysis (n=12). This accuracy number 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. Additionally, the approach assumes that all operational assets are functioning within a nation, or that all assets are documented within our asset database to assign the correct proportion of national production. In some cases, it is understood that assumptions may not be valid such as in the case where an asset is offline for periods throughout the year, which may consequently impact the accuracy in these regions.

We present here three directions for potential improvement of this work. First, the availability of metadata about the cell technology used by assets would allow for a more accurate estimation of process emission, especially those arising from anode consumption and PFCs emissions, as discussed in Huglen and Kvande (2016). Second, emissions estimates could be improved by utilizing more granular aluminum data. One avenue is that of annual, country level data sourced from BGS for sourcing of production values within a specific region. This could result in increased accuracy for the asset-level estimates using the capacity-based disaggregation method. Third, the existence of publicly available alumina refining plant databases would allow us to treat the alumina sector and the aluminum sector independently. This would increase the accuracy of emission estimates since the production location and consumption location of alumina is often different, whereas they are assumed identical in this work. Nevertheless, this work serves as a strong foundational work for the estimation of CO_2 emissions in the aluminum industry which may be utilised to develop more detailed estimates in the future.

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6. Supplementary material

Table 1 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
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

Annex 1: Physical origin of electrolysis direct emissions

CO_2 emissions: Anode consumption

The dominant chemical reaction during the electrolysis process is the following

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

Which corresponds to a theoretical emission factor of 1,222 kg CO_2 per tonne of aluminum. In practice, imperfect current efficiency and additional undesirable reactions increase this emission factor and make it vary slightly from one plant to another (Aarhaug and Ratvik, 2019).

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

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

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.

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

Table 2 Illustration of the method to extract electricity emission factor for France in 2019. The final emission factor obtained by summing the last column is 1.391 t CO_2 /t Al.

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

Annex 3: Summary of all emission factors: two examples

Below is a summary of all the estimated emissions through two selected countries, using 2019 data: France and China.

Table 3 Summary of all emission factors for France in 2019. The PFC emissions were converted using a 100 year horizon for the global warming potential. Total emission factor obtained by summing the last column is 5.058 t CO_2eq /t Al.

Emission source	**Emission type**	**Inputs**	**Emission factor (t CO_2eq/ t Al)**
Anode consumption, CO_2	Direct	Global emission factor	1.514
Anode effect, CF_4	Direct	National PFC emission data and aluminum production	0.160
Anode effect, C_2F_6	Direct	National PFC emission data and aluminum production	0.015

Electrolysis electricity use	Indirect	Regional aluminum power consumption and energy intensity, national electricity emission factors for fossil sources, global emission factors for the others	1.391
Anode production	Direct	Global emission factor	0.324
CPC production	Indirect	Global emission factor	0.3
Alumina refining	Indirect	Regional alumina fuel consumption and energy intensity, global fuel emission factors. Assuming all the alumina consumed in smelters is produced locally.	1.354

Table 4 Summary of all emission factors for China in 2019. The PFC emissions were converted using a 100 year horizon for the global warming potential. Total emission factor obtained by summing the last column is 15.131 t CO_2eq /t Al.

Emission source	**Emission type**	**Inputs**	**Emission factor (t CO_2eq/ t Al)**
Anode consumption, CO_2	Direct	Global emission factor	1.514
Anode effect, CF_4	Direct	Regional emission factor	1.189
Anode effect, C_2F_6	Direct	Regional emission factor	0.146
Electrolysis electricity use	Indirect	Regional aluminum power consumption and energy intensity, national electricity emission factors for fossil sources, global emission factors for the others	9.753
Anode production	Direct	Global emission factor	0.324
CPC production	Indirect	Global emission factor	0.3
Alumina refining	Indirect	Regional alumina fuel consumption and energy intensity, global fuel emission factors. Assuming all the alumina consumed in smelters is produced locally.	1.905