Manufacturing and Industrial Processes sector: Aluminum Production 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. 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 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 70 million metric tonnes in 2023 according to the International Aluminium Institute (IAI, 2025a). A 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, 2025b).

Global aluminum production is responsible for 2% of global human-caused greenhouse gas emissions when accounting for both direct and indirect emissions from electricity generation (GEI, 2022). Aside from carbon dioxide (CO_2) emissions, aluminum is 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).

A clear picture of where aluminum-sector emissions originate and how they are distributed is typically difficult to obtain. As with any such globally traded commodity, 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 aluminum production at the country/regional level (IAI, 2025a; NBSC, 2025) which is often released with substantial delays (~months/years). Only a few jurisdictions, such as the EU and the United States, publish facility-level emissions data (E-PRTR 2024; US EPA 2024).

This methodology aims to close these spatial and temporal gaps by providing global, asset-level estimates of sector-related emissions on a monthly basis. Furthermore, beginning November

2025, Climate TRACE is providing potential emission reduction solutions (ERSs) to understand how sector specific mitigation strategies can reduce emissions for this sector.

2. Materials and Methods

An overview of the aluminum production 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.

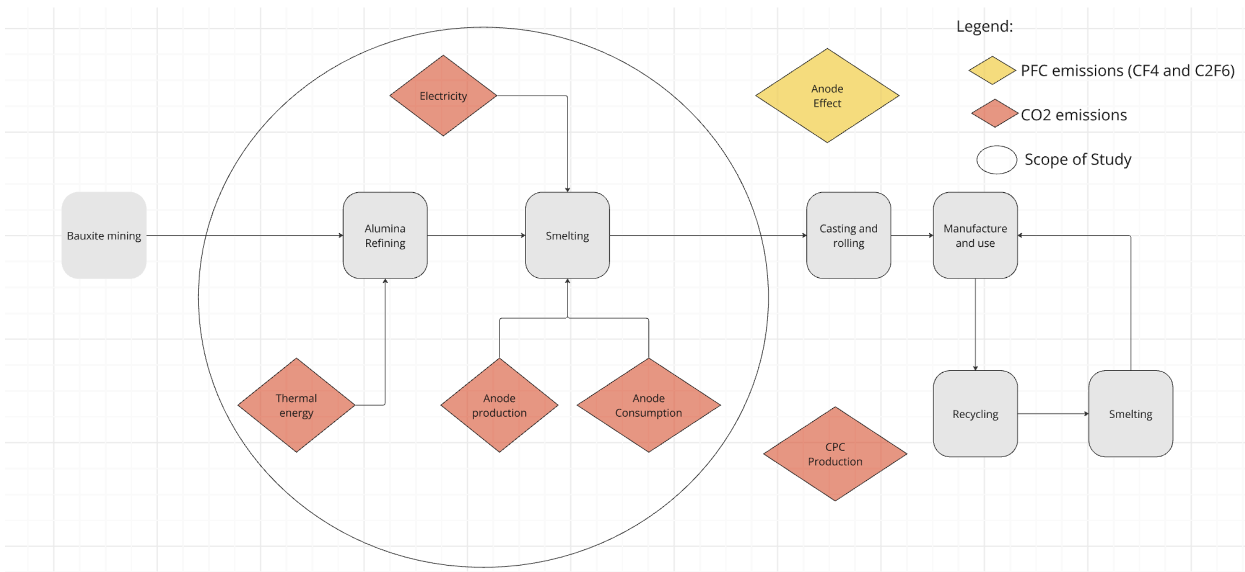

Figure 1 High-level overview of the aluminum sector describing processes and sources of GHG emissions. The scope of this study focuses on primary aluminum production emissions as identified with a circle.

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 oxidised 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 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 aluminum production: the pre-bake process and the 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.

Aluminum is also produced through recycling of scrap metal through smelting. However, in this work we focus on primary production only. Global emissions from the secondary route account for less than 2% of total sector emissions.

2.2 Datasets employed

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

- Process and anode production emission factors (Ecofys, 2009)
- Primary aluminum production, primary aluminum smelting power consumption, alumina production, metallurgical alumina energy intensity and metallurgical alumina fuel consumption aggregated by regions from the International Aluminium Institute statistics (IAI, 2025a).
- Power grid intensities from Ember's monthly electricity data (Ember, 2024)
- Fuel emissions factors from the Energy Information Administration (EIA, 2021)
- Aluminum asset (smelter) database from Light Metal Age (R. Pawlek, 2025)

Currently there is no comprehensive asset or emissions inventory for the refining of bauxite ore into alumina. We developed a large language model to collect alumina assets source data. However, where the results of this model fell well below expected capacity in certain regions, residual capacities sourced from Industrial Info Resources (2025) data were used on an aggregated GADM-2 level.

2.3 Emissions Scope

Greenhouse gas emissions from primary production of aluminum originate from several manufacturing steps and are detailed in Huglen and Kvande (2016). 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 sectoral 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.

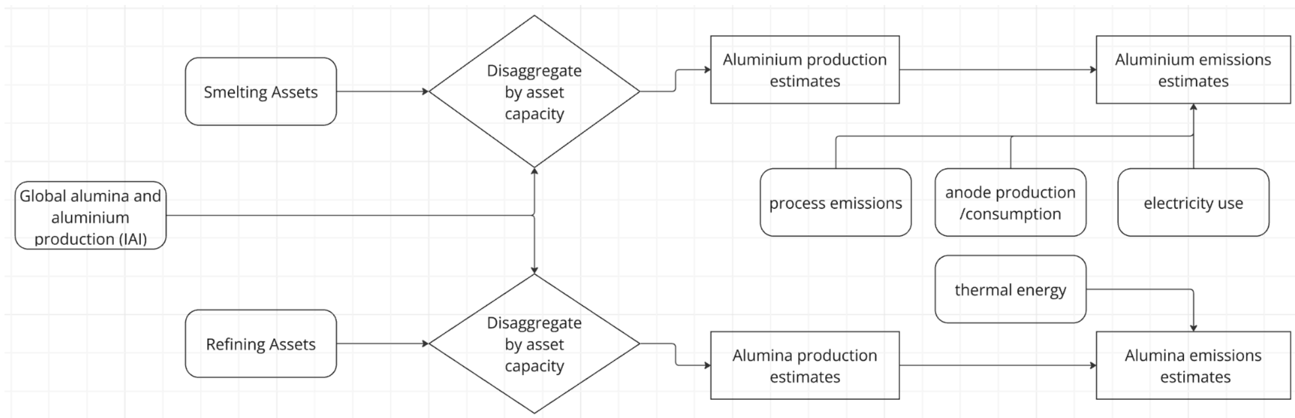

Figure 2 Flowchart of the methodology to calculate facility-level emissions for aluminum smelters and alumina refineries.

2.3.1 Electrolysis process emissions

We use a global emission factor of 2.025 tonnes of CO_2 per tonne of aluminum (t-CO_2/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 (2025a). 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

Emissions from power generation to supply the electrolysis process are by far the largest among total sector emissions, unless very low-carbon electricity (e.g. hydropower) is used. To estimate indirect emissions, we multiply the regional electricity use for smelting (IAI, 2025a) with the local grid intensity (Ember, 2025).

2.4 Generating emissions estimates

The foundation of our emissions estimates is monthly alumina and aluminum production data from IAI (2025a). 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. See below for 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 $P_{B,m}$:

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

Facility-level production is multiplied by the relevant emission factors to estimate point source emissions. Due to aforementioned limitations in sourcing alumina refinery asset information, some emissions are provided regionally, at GADM-2 level (IIR, 2025).

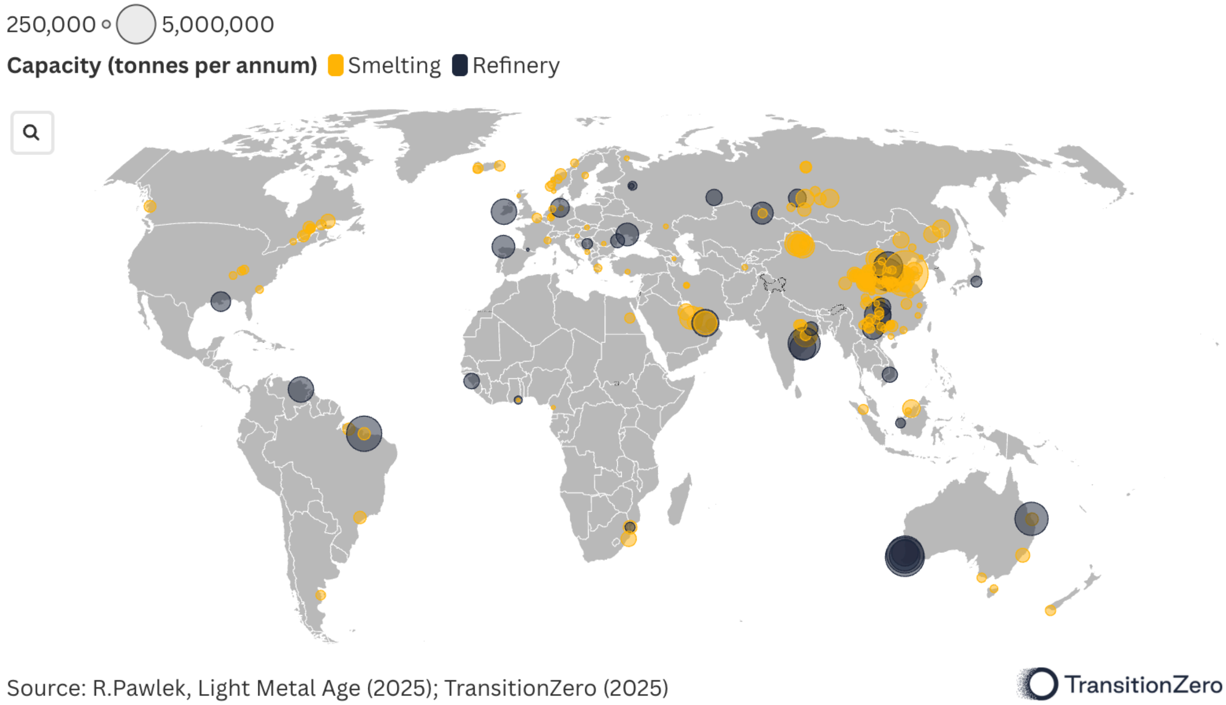

Figure 3 Visual representation of the primary aluminum assets used in this work. Refinery assets are represented by blue circles, whilst smelting assets are represented by orange circles. The circle size reflects the plant capacity as shown top left with the smallest circle = 250,000 and large circle = 5,000,000.

2.4.1 Coverage and emissions covered

Based on 2024 data, asset-level emissions estimates for refineries and smelters accounted for around 63.8% of the sectors' direct emissions (~400 $MtCO_2$). Most of the shortfall comes from a low (~50%) coverage for refineries.

2.5 Emissions Reduction Solutions Overview and Application

Emissions Reduction Solutions (ERSs) for this sector are two strategies: recycled feedstock for smelting and shutdown refineries. *Note: Only rank 1 strategies are provided for assets on the Climate TRACE website and additional strategies will be made available in future releases.*

Recycled feedstock for smelting

The use of recycled aluminum feedstock (secondary inputs) represents a major opportunity for emissions reduction. Recycling aluminum requires only a small fraction of the energy used in primary production and reduces the need for bauxite mining and alumina refining, both of which are highly carbon-intensive (The Aluminum Association, 2022). Electrifying some production processes can further decrease fossil fuel combustion emissions.

By employing recycled feedstock, the emission factor for aluminum production can decrease by approximately 95% compared to primary production (European Environment Agency, 2023). This approach also reduces the need for around eight tonnes of bauxite ore per tonne of aluminum, thereby cutting emissions from raw material extraction. Recycling of aluminum feedstock is widely practiced globally, accounting for more than one-third of total aluminum production in many industrialized economies (The Aluminum Association, 2022). Increased recycling also delivers co-benefits by lowering nitrogen oxide (NO_x) and sulfur oxide (SO_x) emissions from combustion processes (European Environment Agency, 2023).

There are potential caveats and limitations to employing this strategy. First, adoption includes maintaining product quality and managing impurities in recycled inputs. Second, in areas with fossil-fuel-dependent power grids, the emissions reductions from electrified recycling processes may be partially offset by higher indirect emissions from electricity use.

Shutdown refineries

The Shutdown Refineries strategy focuses on the retirement of inefficient or high-emitting aluminum refineries. Some refineries produce higher emissions per tonne of aluminum due to process or equipment type. By shutting down these facilities and reallocating production to other, more efficient refineries, overall sectoral emissions can be reduced while maintaining total production output.

This strategy effectively eliminates 100% of activity and emissions at the decommissioned facility. The associated production activity is then induced at nearby facilities, which generally have a lower emissions factor (i.e., emit less CO_2 per tonne of aluminum produced). In practice, refineries operating above the national average emissions factor are candidates for closure, enabling emissions reductions by diverting activity to more efficient sites.

In principle, this strategy can be implemented anywhere with sufficient capacity at other refineries to absorb the diverted production. Its feasibility depends on the availability of underutilized capacity and the efficiency of alternative facilities. The development of low-emitting, high-capacity aluminum refineries—including those using more efficient technologies or cleaner energy inputs—would enhance the viability of this approach, effectively “pushing out” less efficient plants.

3. Results

Tables 1 and 2 show the largest emitters in the aluminum sector at country and plant level, respectively. China accounts for around 61% of the global primary aluminum production, with some of the largest smelting facilities.

Table 1 Top 10 emitting countries for primary aluminum production (smelting) in 2024

country	direct emissions ($MtCO_2$)	indirect emissions ($MtCO_2$)	total emissions ($MtCO_2$)
China	105.0	333.3	438.4
Russia	10.1	27.6	37.7
India	7.5	30.5	38.0
Canada	7.3	8.0	15.2
UAE	6.2	17.3	23.5
Bahrain	3.6	10.3	13.9
Australia	3.5	12.9	16.4
Brazil	3.2	1.7	4.9
Norway	3.0	0.5	3.6
Malaysia	2.1	7.7	9.8

Table 2 Top 10 emitting aluminum smelters in 2024

plant name	country	capacity (Mt)	total emissions ($MtCO_2$)
Zouping, Shandong	China	6.4	60.9
Fukang, Xinjiang	China	1.9	18.1
Tongshuan	China	1.9	18.1
Xinjiang	China	1.714	16.3
Askar	Bahrain	1.65	13.9
Taweelah Abu Dhabi	UAE	1.628	13.7
Jharsuguda	India	1.725	16.9
Gansu Dongxing Jiujia	China	1.359	12.9
Chiping Shandong	China	1.35	12.9
Wujiaqu	China	1.35	12.9

The majority of smelting emissions are linked to electricity consumption. The share of indirect emissions varies by region, depending on grid intensity—80% in India, 76% in China, and 53% in Canada. In contrast, refineries primarily generate emissions from fossil fuels used to produce heat (Table 3).

Table 3 Top 10 emitting countries for primary aluminum production (refinery) in 2024

country	direct emissions ($MtCO_2$)	indirect emissions ($MtCO_2$)	total emissions ($MtCO_2$)
China	137.2	10.4	147.6
Australia	30.2	2.2	32.4
India	15.1	0.7	15.8
Brazil	13.5	0.2	13.7
Venezuela	7.2	0.6	7.8
UAE	5.3	0.2	5.5
Kazakhstan	3.5	0.2	3.6
Guinea	2.8	0.1	2.9
Russia	2.5	0.2	2.6
Ireland	2.3	0.1	2.4

4. Discussion and conclusions

In this work, we estimate point source emissions for both alumina refineries and aluminum smelters. Our methodology uses asset capacities to allocate a proportional share of the reported national production, multiplied by scopes 1 and 2 emission factors to estimate CO_2. The sources of emissions include anode consumption and production, electricity consumption for electrolysis and fuel consumption for alumina production. This aims to cover more than 90% of greenhouse gas emissions associated with primary aluminum production.

Our method assumes that all assets in a region operate at the same rate in order to assign production according to proportional capacity. It is understood that this may create inaccuracies and will not account for cases where an asset is mothballed/offline for periods of the year. Estimates would be improved by finding a source of more granular production data; province-level data would be particularly useful for China where most production and emissions occur. Nevertheless, this model serves as a strong foundation for the estimation of CO_2 emissions in the aluminum industry with the potential to develop more detailed estimates as more data may become available.

5. Supplementary metadata section

Aluminum 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 aluminum production*
UNFCCC sector equivalent	*2.C.3. aluminum 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	*242 assets across 46 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	aluminum
source definition	emissions from alumina and aluminum 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
location	well-known text (WKT) point location
type	manufacturing method
capacity	monthly plant capacity
capacity_factor	utilisation rate of refinery/smelters
activity	production estimates

Data attribute	Definition
CO2_emissions_factor	direct emissions factor (t-CO2/t-alumina or aluminum)
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 aluminum)
other2	direct and indirect emissions: includes electricity use (t-CO_2)
other3	electricity use factor (MWh/t-alumina or aluminum)
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. ● *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	● *Very low:* Limited or outdated data, and significant uncertainties exist.	Not used; N/A

Data attribute	Confidence Definition	Uncertainty Definition
	● *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.	
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.	±14 to 25 % 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. ● *Very high:* Based on extensive and validated data, providing a very high level of confidence in their precision.	±10 to 15 % of assumed value (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

Data attribute	Confidence Definition	Uncertainty Definition
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.	±21 to 27% 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.	±21 to 27% 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. ● *Very high:* Based on extensive and validated data, providing a very high level of confidence in their precision.	±21 to 27% of emissions estimates

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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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