**LIFE CYCLE INVENTORY DATA AND ENVIRONMENTAL METRICS FOR THE PRIMARY ALUMINIUM INDUSTRY**

**2019 DATA**

***Final***

**November 2022**

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# Introduction

Increased environmental awareness in recent years, driven by regulatory and market demands for improved environmental performance, has given rise to the importance of life cycle assessment (LCA) as a decision-making tool. LCA provides a systematic framework to compile and evaluate the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (ISO 14040). As such, LCA can be used to inform policy, material and design choices as well as provide a foundation to support broader sustainability efforts. The growing importance of LCA necessitates the availability of robust and up-to-date information on key stages in the product system.

The collection of global aluminium industry data for use in LCAs was initiated by the *International Aluminium Institute* (IAI) in 1998, although the Institute has been collecting energy and other relevant data since the 1970s. Life cycle inventory (LCI) data has since been published for the reference years 2000, 2005, 2010 and 2015. The 2014 publication of an Environmental Metrics Report, based on the 2010 LCI, was the first time that the Institute published the results of a cradle-to-gate impact assessment. This analysis brought together the input and output flows identified in the inventory phase, with background datasets, published in third party LCA databases, to evaluate the potential environmental impacts of primary aluminium ingot production, from cradle-to-gate. The 2017 publication of 2015 LCI was the first time that the Institute provided regionalised LCI datasets, which enable users to have access to more specific data for analyses related to regional markets or for the modelling of specific inter-regional flows. In addition to providing such data, the Environmental Metrics Report also demonstrated how such LCI data can be used as part of an impact assessment from cradle to gate through the modelling of a select set of archetype scenarios.

# Goal and Scope

This report builds on the Institute’s Life Cycle work to date and aims to publish all significant life cycle inventory (LCI) data from primary aluminium production processes (Figure 1), from mining of bauxite ore to ingot manufacture, including: raw material inputs, energy and water consumption, emissions to air and water and solid waste generation. The Institute believes that up to date, robust generic inventory data should be made available for use by LCA practitioners to complete independent impact assessments. Also, the inventory provides production weighted mean data that may be used as benchmarks for individual companies to determine significant environmental aspects within their own processes.

This report and accompanying data demonstrate the global aluminium industry’s commitment to reporting its environmental impacts and to ensuring that the latest and most representative LCI data is available for wider use. As such, instead of following the 5-yearly reporting cycle, 2019 LCI instead of 2020 is selected, to avoid the pandemic impact upon the industry’s regular performance. The data included as part of this report provides the highest quality reference material available for conducting life cycle assessments of (primary) aluminium containing products. This report only applies to the raw materials acquisition stage (cradle to gate) of the life cycle of primary aluminium containing products. The inventory data can be used as modules for LCA studies of product systems.

Diagram

Description automatically generated

**Figure 1: primary aluminium production processes**

This report covers the four main phases of an LCA as outlined in ISO 14040 and 14044:

1. Goal and Scope
2. Inventory Analysis
3. Impact Assessment
4. Interpretation

The study has undergone an interactive **independent third-party critical review** by LCA experts (Rolf Frischknecht, Hongtao Wang and Kurt Buxmann) to ensure the methods, data and interpretations of this study are reasonable, consistent with relevant international standards and valid.

# Life Cycle Inventory (LCI)

## Scope of Data

LCI is to determine inputs and outputs of environmental relevance associated with production of primary aluminium from mine to casthouse at a global and, where possible, regional level (Table 1). The full inventory is available in Appendix A.

Primary aluminium production includes the following five unit processes:

1. Bauxite mining;
2. Alumina production (from bauxite);
3. Anode production (including production of *Prebake* anodes and *Søderberg* paste);
4. Electrolysis (including *Prebake* and *Søderberg* technologies);
5. Ingot casting (no differentiation is made between ingot forms).

Unit processes, their relationship to each other and an overview of material input flows are described in Appendix B.

The primary aluminium production process can be summarised as follows:

1. Aluminium-containing ores (bauxites) are mined, predominantly at shallow depths using open cast methods;
2. Aluminium oxide (alumina) is extracted from bauxite through a thermo-chemical digestion process, leaving a waste product comprising the remaining mineralogical contents of the ore;
3. An electrolytic process reduces the alumina into its constituent elements oxygen, emitted as CO2 by reaction with a carbon anode, and aluminium, collected as liquid metal;
4. This molten aluminium typically is cast into ingots, the usual form suitable for further fabrication of semi-finished aluminium products.

|  |  |  |
| --- | --- | --- |
| Region Name | Region Code | Participated Countries |
| Global | GLO |  |
| Africa | AFR | South Africa, Mozambique, Guinea, Egypt |
| Asia ex China | OAS | India, Kazakhstan, Turkey |
| Canada | CAN | Canada |
| China | CNA | China |
| Europe (West & Central) | EUR | Germany, Greece, France, Iceland, Norway, Spain, Sweden |
| Gulf Cooperation Council | GCC | Bahrain, Oman, Qatar,  Saudi Arabia, UAE |
| North America | NAM | Canada, USA |
| Oceania | OCA | Australia  New Zealand |
| Russia and East Europe | ROE | Montenegro, Russia, Slovenia, Slovakia, Ukraine |
| South America | SAM | Argentina, Brazil, Jamaica,  Guyana, Venezuela |

**Table 1: IAI LCI Regions 2019**

Background processes are specified in the flow diagram in Appendix A. These processes have the potential to contribute much greater environmental impact than the unit processes within it. Such additional background processes (in particular supply of fuel and electricity, and production of ancillary raw materials such as pitch and caustic soda) are included in the LCI. Life cycle practitioners who use the LCI data from this study may include elementary flow data for such additional unit processes from life cycle databases.[[1]](#footnote-2) Chapter 4 will demonstrate how such data can be used as part of an impact assessment or information module.

Electricity is a significant input to the aluminium production process and as such, special care is needed to include the appropriate electricity supply mix. Often, the industry electricity supply mix differs from the national or regional grid mix (due to captive or directly delivered power supplies). To ensure that such differences are taken into consideration, data on power sources collected directly from aluminium smelters have been considered for this study. These data are published annually by the IAI at https://international-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/.

Year 2019 data, regionalised according to this report, are replicated in Table 2, with a historical perspective (1980-2019) on global power mix illustrated in Figure 2.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| % power mix | AFR | OAS | CAN | CNA | EUR | GCC | NAM | OCA | ROE | SAM | GLO |
| Hydro | 51 | 3 | 100 | 10 | 61 | 0 | 82 | 30 | 94 | 80 | 26 |
| Coal | 49 | 97 | 0 | 80 | 10 | 0 | 14 | 67 | 2 | 0 | 55 |
| Oil | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Natural Gas | 0 | 0 | 0 | 0 | 4 | 100 | 1 | 1 | 0 | 20 | 11 |
| Nuclear | 0 | 0 | 0 | 0 | 9 | 0 | 1 | 0 | 4 | 0 | 1 |
| Other Renewable |  |  |  | 10 | 13 |  | 2 | 3 |  |  | 7 |
| Other non-renewable |  |  |  |  | 2 |  |  |  |  |  |  |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

**Table 2: Year 2019 aluminium industry power mix data**

**Figure 2: Global aluminium industry power mix for years 1980 – 2019**

Fuel consumption data (hard coal, diesel oil, heavy oil; natural gas) and the direct carbon dioxide emissions not associated with fuel combustion (e.g. process emission from anode consumption) are documented in this inventory; indirect carbon dioxide emissions, such as those associated with power generation, are not included in the inventory but can be calculated using the reported MJ electricity, relevant power mix and appropriate background data from alternative databases as demonstrated in Chapter 4.

## Data Selection

This report contains data for the calendar year 2019 for all unit process. Bauxite residue data for 2015 are also included for selected sites that did not report data for the year 2019 but are still in operation. Data reported as part of the 2015 LCI survey are used as a proxy for sites where the process is unlikely to have changed significantly, but applied to the 2019 production levels to account for changes in production weighting across the industry.

Selection of data categories for this inventory is based on their environmental relevance, either specific to primary aluminium production or as generally acknowledged environmental issues. These data are listed along with explanatory notes in Appendix B. Material flows going into and out of the aluminium processes higher than 1% of the total mass flow (t) or higher than 1% of the total primary energy input (MJ) are included.

## Reference Flow and Allocation

For each unit process, the reference flow is 1,000 kg of product. For the whole primary aluminium production process, the reference flow is 1,000 kg of primary aluminium ingot.

For the ingot casting unit process, the reference flow has been specified to exclude the contribution of aluminium scrap which is purchased in addition to run-around scrap. The overall average from the survey results for the ingot casting process therefore yields a higher mass output (1,030 kg) than the corresponding electrolysis metal input (942 kg), due to a “cold metal” contribution from remelt (51 kg remelt ingot) and recycled (22 kg external scrap) aluminium. This cold metal contribution is excluded by adjusting all inputs and outputs from the survey average by a factor of 0.93, calculated as follows:

(electrolysis metal + alloy additives) / (total metal input – scrap output sold)

(942 kg + 14 kg) / (1,030 kg – 1 kg) = 0.93

In line with the ISO standards on LCA (14040 and 14044), a mass allocation approach is applied to the data reported for the ingot casting process whereby the inputs and outputs are multiplied by 0.93.

There are no significant co-products associated with the unit processes outlined for aluminium production. However, a number of alumina refineries do produce a small amount of non-metallurgical grade alumina (typically <10% production) in addition to metallurgical grade alumina. The input and output data for these processes are not separated into two distinct sub processes and as such data reported by these plants are allocated by mass.

For data on recycling processes and their environmental impacts, please refer to datasets published by regional associations (The Aluminum Association, 2022; European Aluminium, 2018).

## Primary Aluminium Production Mass Balance

This section describes the main component distribution of the global mass flow to 1,000 kg primary aluminium output from extraction of bauxite.

Global average input mass of bauxite for production of alumina (aluminium oxide) is 2,685 kg. This typically includes a significant water component of around 10-20% (c.200-500 kg). Part of the bauxite ore is deposited as bauxite residue (1,220 kg) or recycled (12 kg). The mass of material output from the alumina production process is thus around 1,000-1,300 kg, depending on moisture content of the alumina.

Aluminium oxide (alumina) is chemically reduced in the electrolysis process as follows, with a stoichiometric minimum requirement of 1,889 kg Al2O3 per 1,000 kg of primary aluminium.

2 Al2O3 + 3C = 4 Al + 3CO2

While the majority of the oxygen in alumina fully reacts with the carbon anode to form carbon dioxide, some forms carbon monoxide (which subsequently forms CO2 with oxygen from the atmosphere). Thus, average gross anode consumption (500 kg) is higher than the theoretical mass predicted by stoichiometric analysis (333 kg).

## Geographic System Boundary

The scope of this report is global, with further regional breakdown by unit process where allowed by sufficient reporting from sites to ensure confidentiality. At the global level, data for the Chinese aluminium industry are included for the following LCI flows:

* Anode consumption
* Energy input
* PFC emissions

Unfortunately, data of sufficient quality are not available for other LCI flows from the Chinese aluminium industry, which represented around 56% of global production in 2019. The geographical survey coverage is discussed further in Section 3.7.

## Data Collection

Data were collected through surveys of IAI member and reporting companies:

* 2019 Life Cycle Survey (5-yearly[[2]](#footnote-3)) covered all required LCI data except those already collected through established, annual IAI surveys;
* 2019 Bauxite Residue Survey (5-yearly[[3]](#footnote-4)) gathered data on the production, storage and reuse of bauxite residue;
* 2019 Energy Survey (annual) of alumina production, electrolysis, anode production and casting processes;
* 2019 Anode Effect Survey (biennial) used to calculate perfluorocarbon emissions estimates from the electrolytic process.

Survey forms (Appendix C) were sent out to reporters in Q4 2020 requesting data for the 2019 period. The values reported were assessed alongside previously reported values (normalised per tonne of relevant product) to identify anomalous figures, either as a function of deviation from the 2015 data distribution (+/- 15%) or substantial change within facilities over time. Anomalous data were queried and confirmed or amended by survey respondents. In some cases, where data could not be verified by the reporter, the Secretariat made the decision to either exclude (+/- 2 SD or >15% deviation per tonne from 2015) or make assumptions to amend the data where possible e.g. reporter unit errors. Where necessary, the Secretariat also made assumptions about non-reporting for selected data points (See Section 2.9). In these instances, if a respondent reported data for an input/output flow with an array of answers, answers in the array that were left blank were replaced with zero values.

## Survey Coverage

Figure 3 illustrates the coverage of LCI and Energy Survey data for 2019 alumina production, per region. Response rates using the relevant global or regional production figures as the denominator are available for each individual data point in Appendix A.

The Chinese aluminium industry (accounting for 54% and 56% of the world’s 2019 alumina and primary aluminium production respectively) currently reports energy data to the IAI on an aggregated China-wide basis (via the China Nonferrous Metals Industry Association). This forms the basis of Chinese energy data published annually by the IAI (<http://www.international-aluminium.org/statistics)> and included Figure 2. 2019 LCIs, for the first time, include facility specific energy data from China industry, which has improved the statistical accuracy for this important region.

Data on PFC emissions directly measured at a sample of Chinese smelters between 2008 and 2013, forms the basis of assumptions of Chinese emissions performance, as reported in the IAI’s annual Anode Effect Survey Reports (https://international-aluminium.org/statistics/perfluorocarbon-pfc-emissions/).

PFC measurements made on the modern cells brought to light the fact that PFC emissions can, and do occur, outside those times when the cell is on anode effect with average cell voltage exceeding the defined trigger voltage; eight volts for many cell technologies. This realisation has resulted in redefining these emissions into two categories - high voltage (HV) PFC emissions and low voltage (LV) PFC emissions. By following the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, PFCs contained in this report includes emissions from anode effects at both high and low voltages.

**Figure 3: Response rates LCI (Alumina) and Alumina Energy 2019 by region**

**Figure 4: Response rates LCI (Electrolysis) and Electrolysis Energy 2019 by region**

## Technology Coverage

Alumina production process data included in the LCI are reported by facilities that refine metallurgical grade alumina from bauxite ores only. It is estimated that less than 5% of global alumina production was derived from non-bauxite sources in 2019. Stand-alone chemical-grade alumina plants, alumina from nepheline processing and alumina from other sources are outside of the scope of this report.

The aluminium electrolysis unit process data included in the LCI are reported by facilities operating all existing major technologies, which can be broadly grouped according to anode type: *Prebake* and *Søderberg*. Around 12% of the total aluminium production covered by LCI survey reporting was produced using *Søderberg* technologies, with the remaining 88% from *Prebake* facilities. This is not reflective of the global technology split which is 95% *Prebake* and 5% *Søderberg;* Chinese facilities only employ *Prebake* technologies.

During the process of regionalisation, it became clear that publication of LCI data on *Søderberg* technology was still required but efforts needed be made to maintain reporter confidentiality; a challenge with so few reporting *Søderberg* sites. LCI data for Søderberg technology was therefore included as a separate global dataset, and at the regional level, data reported from Søderberg facilities was included as part of a the aggregated (*Prebake + Søderberg*) regional average.

## Assumptions for Non-Reporting Production

Assumptions for non-reporting production are made for facilities that did not report in 2019 but are still in operation and reported in 2015. The reported data for these facilities was included on a per tonne of production basis applied to 2019 production levels. Data in the combined Summary inventory in Appendix A (per tonne of primary aluminium ingot) however, is calculated based on the year 2019 global production weighted technology split between *Prebake* (95%) and *Søderberg* (5%) cell technologies. This therefore assumes a non-reporting industry (including China) per technology performance equivalent to the reporting industry.

There are four key areas in the LCI where assumptions are made in the unit process data for input/output flows which have an array of options and for which non-reported data points should in effect be equal to zero:

* **Sea water use**: non-reporting is assumed to be equivalent to zero values from plants that are not located by the sea;
* **Transport:** non-reporting for certain transport modes is assumed to be equivalent to zero values given that not all facilities have equal access to rail, road or sea transport;
* **Fuel and power mix**: non-reporting for certain fuel sources is assumed to be equivalent to zero values as the fuel and power mix of the industry as a whole is the relevant average.
* **Land use type**: non-reporting for certain land use types is assumed to be equivalent to zero values given that not all facilities use all land types.

## Data Analysis

### Data Quality

Quantitative data quality indicators (DQI) are calculated against each data point as follows:

* Representativeness (weighted mean values):all values presented in the text of this report represent production weighted mean values for aluminium processes;
* Completeness: all values presented in this report have a % production coverage value calculated; and
* Variance: standard deviation, minimum and maximum values.

### Averaging

A normal distribution of data is assumed. The following is a summary of the methodologies used for averaging of inventory data.

#### Production Weighted Mean

A production weighted average is a reflection of given reported process input or output data normalised per tonne of product for those facilities that reported the relevant process input or output. Reporting production is only included in the denominator if data were reported (including zero values) for inclusion in the numerator. Non-reported or “blank” data points are not included in the numerator or the relevant production denominator.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | A | B | C | D |
| 1 | **Plant** | **Production tonnage (t)** | **Emission (kg)** | **Emission Rate (kg/t)** |
| 2 | **U** | 10 | 30 | 3 |
| 3 | **V** | 20 | 0 | 0 |
| 4 | **W** | 10 |  |  |
| 5 | **X** | 25 | 42 | 1.68 |
| 6 | **Y** | 100 |  |  |
| 7 | **Z** | 300 | 60 | 0.2 |
| 8 | **TOTAL** | 465 | 132 | 0.37 |

**Table 3:** **Example data for explanation of Weighted Mean**

Weighted Mean = SUM (C2:C7)/SUMIF (C2:C7,” <>” &””, B2:B7)

(using Microsoft Excel function syntax) = (132)/(10+20+25+300)

= 132/355 = **0.37 kg/t**

#### Aluminium Weighted Mean

The above weighted mean, but expressed per tonne of aluminium by multiplication by mass weighted factor.

*Example:*

0.37 kg emissions per tonne of bauxite produced

5.6 tonnes of bauxite required per tonne of aluminium produced

0.37 \* 5.6 = **2.07 kg** bauxite related emissions per tonne of aluminium produced

## Changes in Inventory Data from 2015 to 2019

Changes (or lack thereof) in inventory data between the 2015 and 2019 datasets can be broadly accounted for by the factors outlined below:

* **Data Driven Differences:** changes in the composition of the reporting cohort, the quality of survey responses or reporting rates can contribute to differences between the 2015 and 2019 inventory. Such occurrences should mean that users of the inventory should be aware that apparent trends over this period are not definitive and can sometimes be considered unreliable.
* **Performance Driven Differences:** real changes in global and/or reporting industry performance over the period. Such differences tend to be driven by incremental improvements in process management, the addition of new capacity, retrofitting of existing capacity and/or closure of older facilities as well as changes in raw material quality.
* **Methodology Differences:** changes in correspondence to the methodology development. Such as accounting for emissions from anode effects at both high and low voltages by following the latest IPCC Guidelines development.

### Bauxite Mining

#### Data Driven Differences

***Freshwater input and output*** is collected from 12 facilities across 5 countries, whilst the 2015 data was collected from 11 facilities from 3 different countries. The average freshwater consumption has increased from 2.5 m3/t Al ingot to 3.4 m3/t Al ingot, although some mines reported for both 2015 and 2019 decreased freshwater consumption.

***Sea water input and output*** is respectively 1.3 m3/t Al ingot and 1.2 m3/t Al ingot compared to zero in 2015. No facility reported sea water input and output in the 2015 survey. But two facilities reported for 2019. These data are only of minor environmental relevance and do not contribute to the water footprint.

***Fuels and electricity consumption*** are different from 2015, with an increase in coal and electricity input and a decrease in heavy oil input. These changes are a consequence of increased reporting coverage for coal. 17 facilities from 7 countries responded to the 2019 survey, whilst 11 facilities from 3 countries reported for 2015 survey. It should be noted that energy consumption is very small in the mining process compared to subsequent thermal and electrochemical unit processes.

**Air emissions** of **sulfur dioxide** and **nitrous oxides**, as well as **overburnden** are included in the inventory for the first time for 2019 reference year.

#### Performance Driven Differences

***Land occupation*** related to bauxite mining have been included for the first time in the 2015 inventory. Land occupation is doubled from 2015 to 2019, although the average occupation time is dropped by 37%.

***Particulate air emissions*** appear to be up by 62%. The rise is mainly caused by the sites in Oceania. Also a new site joined the 2019 survey reported high particulate emission rate.

***Mine solid waste***has decreased since 2015 by 23%, which is also driven by the sites in Oceania. The rest sites that reported to both 2015 and 2019 surveys maintained a stable performance.

### Alumina Production

#### Data Driven Differences

***Particulate emissions*** have decreaseddue to increased reporting facilities, from 15 refineries in 8 countries to 22 refineries in 11 countries. Facilities that reported to both 2015 and 2019 surveys, some have reported increased particulate emissions.

***Freshwater input and output*** is collected from 23 facilities across 12 countries, whilst the 2015 data was collected from 16 facilities from 8 different countries. The average freshwater consumption has increased from 1.2 m3/t Al ingot to 5.4 m3/t Al ingot.

***Sea water input and output*** is reported by more facilities for 2019 as there was only one facility reported sea water input and output in the 2015 survey.

***SF6 emissions into the air*** have been included for the first time in the 2019 inventory.

***Bauxite residue recycled*** decreased between 2015 and 2019. There is ongoing research of bauxite residue utilisation, but mass application of bauxite residue in commercial applications (e.g. cement production, refractories and landfill covering) takes time. Further details on bauxite residue management are available on the IAI’s website.

#### Performance Driven Differences

***Energy mix***

Differences in energy mix between 2015 and 2019 data are summarised in Table 4. The data indicate a reduction in energy consumption of each type of energy. The change is largely driven by the region of Asia and North America.

|  |  |  |  |
| --- | --- | --- | --- |
| Fuel Type | Unit | 2019 | 2015 |
| Heavy oil | MJ/t Al2O3 | 842 | 1,063 |
| Diesel oil | MJ/t Al2O3 | 7 | 44 |
| Natural Gas | MJ/t Al2O3 | 2,478 | 2,745 |
| Coal | MJ/t Al2O3 | 6,414 | 6,927 |
| Electricity | MJ/t Al2O3 | 547 | 786 |
| Other | MJ/ t Al2O3 | 168 |  |

**Table 4: Life cycle inventory alumina energy mix data for years 2015 and 2019**

**Figure 5: Global alumina industry energy mix for years 2010 – 2019**

***Transport*** distance increased among all three ways of transportation, which reflects the shift taken place in the global bauxite supply chain.

***Sulfur dioxide emissions, Suspended solids, Mercury water emissions*** and ***Oil and grease/total hydrocarbons*** received survey responses from a similar reporting cohort between 2015 and 2019. Therefore, the data differences ares purely driven by the performance of the reporting facilities.

|  |  |  |  |
| --- | --- | --- | --- |
| **Inventory Flow** | **Unit** | **2019** | **2015** |
| ***Sulfur dioxide emissions*** | kg/t Al ingot | 1.4 | 2.2 |
| ***Suspended solids*** | kg/t Al ingot | 0.15 | 0.08 |
| ***Mercury Water Emissions*** | g/t Al ingot | 0.0003 | 0.0009 |
| ***Oil and grease/ total hydrocarbons*** | kg/t Al ingot | 1.6 | 3.2 |

**Table 5: Life cycle inventory alumina data differences for year 2015 and 2019**

***Other solid industrial waste*** increased by 33%, the increase is caused by existing reporting facilities, as well as new facilities joined the 2019 survey.

***Energy consumption***

Comparing the global alumina (including China) industry fuel mix from 2015 to 2019, energy intensity of the process has actually decreased by 10%. This is not a reporting difference and represents a real change in the industry’s energy consumption per tonne of product. This demonstrates the industry’s continuing effort of improving energy efficiency.

**Figure 6: Global energy intensity of the alumina production process for years 2010 –** **2019**

#### Methodology Differences

***Calcined lime*** consumption in addition to purchased lime, takes on-site produced lime into account. By following the updated accounting, 2015 lime consumption should be 52kg/t alumina, which is similar to the 2019 surveyed result.

### Anode Production, Electrolysis & Ingot Casting

#### Data Driven Differences

***Alumina’s Transport distance by rail*** increased significantly as the reporting facilities have increased from 5 smelters in 3 countries to 24 smelters in 7 countries.

***Freshwater consumption (input-output)*** has increased from 2.3 m3 H2O/t Al in 2015 to 5.6 m3 H2O/t Al in 2019. ***Fresh water input*** and ***output*** have a number of uncertainties associated with reported values, reflecting differences in facilities’ measurement of freshwater use and consumption. In some cases, sites with comprehensive water measurement systems are able to report disaggregated water data. For many however, freshwater input and output data for anode production, electrolysis and ingot casting are reported as a ‘total plant’ number. An indicative split for freshwater consumption by unit process has been estimated, based on historic trends and from typical usage estimates derived from reporters that submitted separate process data. The number of reporting facilities have increased by more than 1/3, which also has an impact on the results.

***Sea water input*** and***output***has increased since 2015 as the number of reporting facilities have doubled, Sea water input and output of those responded to both 2015 and 2019 surveys remain stable.

|  |  |  |  |
| --- | --- | --- | --- |
| Inventory Flow | Unit | 2019 | 2015 |
| Steel input – anode production | kg/t Al ingot | 5 | 8 |
| Nitrous oxides into air - electrolysis | kg/t Al ingot | 0.6 | 0.3 |
| Polycyclic aromatic hydrocarbons into air - electrolysis | kg/t Al ingot | 0.06 | 0.02 |
| Polycyclic aromatic hydrocarbons into water - electrolysis | g/t Al ingot | 0.02 | 0.37 |
| Benzo(a)pyrene into air | g/t Al ingot | 0.12 | 0.25 |
| Hydrogen chloride into air | kg/t Al ingot | 0.01 | 0.02 |
| Suspended solids into water | kg/t Al ingot | 0.19 | 0.58 |
| Oil and grease/total hydrocarbons into water | kg/t Al ingot | 0.03 | 0.05 |
| Recycled Refractory - electrolysis | kg/t Al ingot | 1 | 6 |
| Waste alumina | kg/t Al ingot | 1 | 4 |
| Filter dust recycled | kg/t Al ingot | 0.2 | 0.53 |
| Filter dust landfilled | kg/t Al ingot | 0.1 | 0.03 |
| Waste carbon or mix - electrolysis | kg/t Al ingot | 16 | 9 |

**Table 6.1: Life cycle inventory data differences for year 2015 and 2019 – Anode Production, Electrolysis & Ingot Casting**

***Steel input*** ,***Hydrogen chloride*** emission**,** output of ***Waste Alumina* a**nd ***Waste carbon or mix*** have decreased due to the expanded reporting cohort. The number of reporting sites has doubled, so has the number of reporting countries. 2019 data is taken as more appropriate.

***Nitrous oxides into air*** from the process of electrolysis has nearly doubled. There were two facilities reported much higher emissions intensity than the rest. Also, number of reporting facilities dropped by 1/3 from 2015 to 2019. In this case, 2015 data is more representative.

The 2015 response rate for ***polycyclic aromatic hydrocarbon*** emissions to air/water for electrolysis was very low (respectively 16% and 6% of global production), and as such the 2019data is with an increased response rate of 18% and 15% by production respectively.

***Benzo(a)pyrene into air*** is in a similar reporting condition as *polycyclic aromatic hydrocarbon*, although response rate by production increased from 4% to 14% for anode production, 6% to 13% for electrolysis, it’s still very low. In such case, 2019 with higher response rate is recommended to be used as appropriate.

***Suspended solids into water*** and ***Oil and grease/total hydrocarbons into water*** from anode production as well as casting was reported byless than 5% of global production for 2015. The 2019 response rate is more than quadrupled, hence the 2019 average results are more reliable.

***Recycled Refractory*** from electrolysisappear to have decreased a lot. There was one site reported very high recycling rate for 2010 and was included in the 2015 dataset. If remove this site, the recycling rate of refectory from electrolysis is similar between 2015 and 2019. Also, it should be noted that bauxite residue recycling is often a cyclical process and therefore annual recycling rates can vary.

Both ***Filter Dust recycled*** and ***Filter Dust landfilled*** received very few response for 2015, 8% and 7% of global production respectively. Response rate increased to 21% and 24% respectively for 2019. Hence 2019 data is more reliable.

#### Performance Driven Differences

|  |  |  |  |
| --- | --- | --- | --- |
| Inventory Flow | Unit | 2019 | 2015 |
| Refractory material input – anode production | kg/t Al ingot | 1 | 3 |
| Chlorine input | kg/t Al ingot | 0.005 | 0.01 |
| Fluoride into water - Electrolysis | kg/t Al ingot | 0.3 | 0.1 |
| Recycled Spent pot lining | kg/t Al ingot | 10 | 17 |
| Spent pot lining for landfilling | kg/t Al ingot | 25 | 8 |
| Recycled Refractory – anode production | kg/t Al ingot | 1.3 | 3.5 |

**Table 6.2: Life cycle inventory data differences for year 2019 and 2015 – Anode Production, Electrolysis & Ingot Casting**

***Refractory material input*** – anode production and ***Chlorine input*** have decreasedas most sites have remained relatively stable or decreased in the use since 2015. New survey participants also reported a lower input than 2015 average.

***Fluoride emissions* *to water*** from electrolysis have nearly tripled from Prebake technologies due to the increased emissions from both Europe and Gulf area. Electrolysis operated in all other regions remained at a stable emission level between 2015 and 2019.

***Spent pot lining*** is the 2nd largest solid waste from the aluminium industry. By comparing the 2015 and 2019 survey results, it appears that Oceania is the only region that made progress in increasing spent pot lining recycling. As more spent pot lining went into landfilling, the 2019 global average is tripled. However, it should be noted that SPL recycling is often a cyclical process, and therefore annual rates can vary. This survey result may not necessarily reflect the actual changes in operational performance.

***Recycled Refractory*** from anode production decreased because recycling reduced in most regions since 2015, Also, some sites with good recycling performance in North America were closed.

#### Methodology Differences

Emissions of the perfluorocarbon (PFC) gas ***tetrafluoromethane*** (CF4) appear to have increased by 41%, mainly due to the inclusion of low voltage (LV) PFC emissions. The latest information on the main methods for measuring LV, HV (including cell start-up, CSU) PFC emissions is outlined in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

If consider HV PFC emissions only, the smelters achieved 10% reduction in emission intensity of CO2e.

**Figure 7: Total global aluminium industry perfluorocarbon emissions (blue curve, exclusive of LV PFC emissions) against global production (green columns)**

## Interpretation

**Goal & Scope:** The purpose of this inventory report is to characterize accurately at the global level, and where possible, the regional level, resource inputs and significant environmental releases associated with the production of primary aluminium from bauxite mining to ingot casting.

This 2019 life cycle inventory is the most accurate and up-to-date of any published on primary aluminium production.

With a continued focus on energy, water use, emissions to air, emissions to water and waste generation, and the inclusion of new inventory flows such as SF6, Other energy input and Overburden in bauxite mining, the coverage of relevant inputs/outputs can be seen to have improved on the 2015 inventory.

The data, methods and interpretation of this LCI have been subject to ongoing, independent, third party review.

Following the feedback from the review of 2015 LCIs, a number of improvements have been made to the following area:

* Incorporate site specific data of the Chinese aluminium industry, hence the 2019 dataset has greatly improved accuracy for energy input (fuel combustion and electricity consumption/power mix) and anode consumption;
* Inclusion of reporting site casthouse mix data (input and output);
* Distinction between input and output flows for metallurgical alumina production and chemical alumina production from refineries that produce both types of alumina.

As in previously published LCIs, the quality of reported data varies significantly between survey questions, depending on reporting rates for each. Reporting rates as a percentage of global or regional production have therefore been included in the data tables (in Appendix A) in order to allow users of the data to evaluate confidence in the results on a data point-by-data point basis. Reporting rates are generally equal to or better than those published in the 2015 LCI, signalling an improvement in the overall quality and representativeness of the 2019 dataset compared to previous years.

Significant differences in aluminium industry smelting process input-output data tend to be a function of technology in use rather than location. Although Chinese LCI data is lacking for a number of inventory flows, China employs 100% point fed prebake smelters and its alumina production technology is considered to be relatively similar to the rest of the world, and so global averages of non-energy input-outputs can be assumed to approximate reasonably the Chinese industry’s performance.

As observed in previous publications, power mix is the most significant influence on primary aluminium environmental impacts and, as such, users of this inventory data should ensure that they utilise aluminium industry specific power mix data where possible.

# Life Cycle Impact Assessment (LCIA)

## Introduction

The Life Cycle Impact Assessment (LCIA) phase is to evaluate potential impacts on ecosystems, humans and aboiotic resources by an industrial process or processes, identified during the Life Cycle Inventory phase.

The **system boundary** for this primary aluminium LCIA has been expanded from the LCI in the previous chapter to include environmental impacts of background processes, such as electricity generation and ancillary materials production, making it a cradle-to-gate assessment.

Impact assessment as used in this study should be considered as an *example* of how the data generated as part of the inventory phase can be used in life cycle assessments. Life cycle practitioners may use alternative methods of impact assessment based on the inventory data in Chapter 2 (or specific supply chain data if available) to conduct their own specific life cycle assessments.

The **functional unit** for this impact assessment is 1 tonne of primary aluminium ingot at the factory gate. All results are provided per tonne of primary aluminium ingot.

The **geographical scope** of this impact assessment is global, with example scenarios illustrating the most significant 2019 inter-regional flows of bauxite to alumina to aluminium, where possible. In order to meet the need for increasingly specific data, IAI’s 2017 Environmental Metrics report provided regional inventories, to equip LCA practitioners with datasets that better reflect the heterogeneity of lifecycle performance that exists across the global industry (predominantly driven by different energy sources), plus, *example* scenarios of primary aluminium production from mine to casthouse by utilising the regional datasets at the impact assessment phase. This report will continue such practice.

## Methodology

### Selection and Definition of Impact Categories

The impact categories included in this study are aligned with previously published primary aluminium industry data (IAI 2017) and are in accordance with guidance on LCA methodologies for Metals (PE International 2014). The LCIA methodology followed in this assessment is CML 2001 (Jan 2016), with the following impact categories selected:

* Acidification potential
* Depletion of fossil energy resources
* Eutrophication potential
* Global warming potential
* Ozone depletion potential
* Photo-oxidant creation potential

In addition, “water scarcity footprint” (WSFP), as outlined in ISO 14046, has been selected. IAI has supported the development of the water scarcity footprint methodology for primary aluminium, in light of increasing awareness around water use impacts across the resource sector. Available Water Remaining (AWaRe) replaces Water Stress Index (WSI) as the water scarcity characterisation factors, AWaRe is a new consensus method of UN Environment working group on water use in LCA (WULCA), which was released in 2015 and is suggested by JRC as new standard impact assessment method for water use in PEF.

For the determination of the direct water footprint, the characterization factors according to AWaRe have been determined plant by plant. Then the water consumption has been multiplied by this site-specific characterization factor. For the same location, the AWaRe characterization factor is by a factor 20 – 200 higher than the WSI characterization factor which has been used for the 2015 LCA report.

A breakdown of the relative contribution to greenhouse gas emissions of primary aluminium production unit processes is also included. For a complete description of selected impact categories see Appendix D.

Land use is not included as an impact category, although inventory data for land occupation and transformation related to primary aluminium processes are published here. Human toxicity and ecotoxicity are not included as impact categories here, as the complex methodologies for their quantification, with respect to metals, are not thought to be robust enough at present. The aluminium industry, through the International Aluminium Institute, continues to support research to develop better methodologies and to test them using aluminium industry data and it is hoped that in future it will be possible to include such impact categories.

### Classification and Characterisation of LCI Results

As described in ISO 14044, the assessment of potential environmental impacts is divided into two steps, which must be performed as a minimum:

1. Classification: assigning life cycle inventory results to life cycle impact categories (*classification*).
2. Characterisation: application of science-based factors to the classified life cycle inventory results which when summed for each impact category give the category indicator results

The two steps can be completed simultaneously using software tools to produce LCIA results. The LCIA results were modelled in GaBi version 2022.2. The data used in the GaBi database for characterisation are published by reputable and internationally recognised organisations including:

* *International Organization for Standardization* (ISO);
* *Society of Environmental Toxicology and Chemistry* (SETAC);
* *World Meteorological Organisation* (WMO); and
* *Intergovernmental Panel on Climate Change (IPCC).*

### Mass Flow Analysis (MFA), Key Supply Chains and Scenario Selection

In addition to modelling the global aluminium industry’s average potential environmental impacts, a selected set of archetypal scenarios is modelled, to demonstrate how the regionalised inventory data can be used by practitioners to describe representative primary aluminium cradle-to-gate impacts along the value chain.

To define these scenarios, major material flows by unit process for 2018 and 2019 were analysed, using the International Aluminium Institute’s mass flow model. A visualisation of the inter-regional flow of bauxite, alumina and aluminium (primary and scrap), from years 1962 to the present, can be found at https://alucycle.international-aluminium.org/). This tool can be used to support life cycle assessments that require data on market supply by region.

In this analysis, four scenarios have been chosen to reflect the most significant inter-regional material flows, as well as to provide examples across a range of regions. They thus also address issues that can arise with respect to modelling regions with different levels of reporting coverage and background data availability.

Insufficient reporting coverage for some regions (e.g. China) means that the global dataset is used as a proxy. For bauxite mining, a global level dataset is made available as differences between regions are small and bauxite mining is a relatively minor contributor to the environmental impacts addressed in this report. This should be reviewed in future iterations as the significance of processes can change for different indicators e.g. land use. The scenarios are outlined in Table 7 with details on the relevant LCI and Energy survey dataset used to model each. By this approach, sets of cradle-to-gate indicator results are determined for China, GCC, Europe and Canada. Figure 8 shows the all-China scenario 1, based on the MFA.

Although trade data were used in the mass flow analysis to inform the selection of scenarios, material imports/exports are not considered in the impact modelling phase. Therefore, the results presented here do not reflect the environmental impacts of the material supply available in each of these regions but rather the production of material at each unit process that occurs within these regions. Cradle-to-grave regional life cycle assessments have been published (The Aluminum Association, 2021; European Aluminium Association, 2018), which do take material imports into consideration and therefore provide environmental impact assessments that reflect the impacts associated with material supply in their respective regions.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Bauxite Mining** | **Alumina Production** | **Anode production, Electrolysis and Casting** |
| **Scenario 1** | **China (CNA)** | **China (CNA)** | **China (CNA)** |
| *LCI Dataset* | *Global (GLO)* | *Global (GLO)* | *Global (GLO)* |
| *Energy Dataset* | *Global (GLO)* | *China (CNA)* | *China (CNA)* |
| **Scenario 2** | **Oceania (OCA)** | **Oceania (OCA)** | **Gulf Cooperation Council (GCC)** |
| *LCI Data* | *Oceania (OCA)* | *Oceania (OCA)* | *Gulf Cooperation Council (GCC)* |
| *Energy Data* | *Oceania (OCA)* | *Oceania (OCA)* | *Gulf Cooperation Council (GCC)* |
| **Scenario 3** | **Africa (AFR)** | **Europe (EUR)** | **Europe (EUR)** |
| *LCI Data* | *Global (GLO)* | *Europe (EUR)* | *Europe (EUR)* |
| *Energy Data* | *Global (GLO)* | *Europe (EUR)* | *Europe (EUR)* |
| **Scenario 4** | **South America (SAM)**  I’ve b | **South America (SAM)** | **Canada (CAN)**  I’ve b |
| *LCI Data* | *South America (SAM)* | *South America (SAM)* | *Canada (CAN)* |
| *Energy Data* | *South America (SAM)* | *South America (SAM)* | *Canada (CAN)* |

**Table 7: Example archetype scenarios considered for impact modelling**

**Diagram

Description automatically generated**

**Figure 8: Mass flow example Scenario 1 – China**

### Impact Modelling

A primary aluminium cradle-to-gate model was initially developed as part of the impact modelling process for 2010 data; this model provides the foundation for the current impact assessment. The global model has been adjusted as follows, prior to the update with 2019 inventory data (foreground data):

* Electricity supply: inclusion of net losses as a parameter
* Update of the petroleum coke dataset to calcined petroleum coke
* Anode consumption net values is replaced by gross consumption, with butt values
* Low voltage PFC emissions is added by following the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories
* Split the refining module into digestion and calcination

The background datasets are from GaBi version 2022.2. The scenario models are adapted from the global model by using the appropriate regional (or global) inventory and energy datasets of each unit process.

Appendix F provides the recalculated LCIA results of 2015 LCIs at global level.

In the absence of region-specific foreground data for regions such as China, global level data are used as a proxy. Collecting inventory (foreground) data for China, beyond energy consumption, remains a challenge but as Chinese capacity is exclusively point fed prebake technology, the use of global averages for prebake technology is reasonable. Datasets on electricity consumption, power mix, thermal energy and perfluorocarbon emissions, the most significant drivers of environmental impact, are available at a regional level for all scenarios and are incorporated into the scenario models.

Figure 9 outlines how the primary aluminium data were modelled in GaBi version 2022.2 (using the global dataset). Electrolysis process impacts from Søderberg technology are only modelled at the global level. As discussed in Section 2.8, Søderberg smelter output only accounted for 5% of global production in 2019 and so data have not been disaggregated in the regional datasets to maintain reporter confidentiality.

In addition to the inventory data related to the aluminium processes collected as part of the IAI surveys, background datasets related to auxiliary processes are integrated and updated in the model. These datasets are included in GaBi version 2022.2 and include:

* Limestone production (EU-28, 2021)
* Caustic soda production (EU-28, 2021)
* Calcined petroleum coke production (EU28, 2021)
* Pitch production (DE, 2021)
* Aluminium Fluoride production (EU28, 2021)
* Electricity and fuel supply systems (2018)
* Transportation (GLO, 2021)

**Timeline

Description automatically generated**

**Figure 9: GaBi plan for global model**

### Electricity Generation

Primary aluminium production (in particular, electrolysis and alumina refining processes) is an energy intensive process. IAI previous studies show that, at the global level, electricity is the most significant influence on environmental impact category indicator results for primary aluminium production. As such, it is important to represent accurately electricity consumption in the electrolysis process, which accounts for the largest percentage of total electricity consumption at the global level (>90%).

An industry specific electricity model was updated within the GaBi database for the electrolysis process. Grid loss has been considered. The model is based on regionalised power consumption data as reported by industry respondents as part of the IAI 2019 annual energy surveys (See Table 8). Inclusion of an industry-specific electricity mix by region is important as regional or national grid mixes often do not reflect the power mix of the aluminium industrial consumer.

Regional background datasets, corresponding to the regions included in each scenario are developed from existing LCI data in GaBi against each energy carrier. Proxy data is used for regions with limited data – e.g. South Africa data used for other African countries.

**Table

Description automatically generated**

**Figure 10: GaBi plan for electricity modelling in the global model**

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Africa | Asia  (ex. China) | China | Europe West & Central | GCC | North America | *Of which Canada* | Oceania | Russia  & East Europe | South America | World |
| Hydro | 11,651 | 1,264 | 48,434 | 30,420 | 0 | 45,169 | *(42,165)* | 8,229 | 62,635 | 13,492 | 221,294 |
| Coal | 11,320 | 39,203 | 387,474 | 4,940 | 0 | 6,193 | *0* | 18,547 | 1,212 | 0 | 468,891 |
| Oil | 0 | 5 | 0 | 289 | 6 | 5 | *0* | 0 | 4 | 0 | 309 |
| Natural Gas | 0 | 0 | 0 | 1,934 | 84,347 | 428 | *0* | 263 | 128 | 3,384 | 90,485 |
| Nuclear | 0 | 0 | 0 | 4,499 | 0 | 137 | *0* | 0 | 2,760 | 0 | 7,395 |
| Other Renewable | 0 | 37 | 48,434 | 6,598 | 0 | 885 | *0* | 809 | 155 | 84 | 57,003 |
| Other non-renewable | 19 | 0 | 0 | 837 | 0 | 23 | *0* | 26 | 46 | 17 | 968 |
| Total | **22,990** | 40,510 | 484,342 | 49,517 | 84,353 | 52,841 | ***(40,456)*** | 27,873 | 66,941 | 16,977 | **846,345** |

**Table 8: 2019 Power Mix by Region (GWh)**

The data in Table 8 differs from the power mix reported in <https://international-aluminium.org/statistics/primary-aluminium-smelting-power-consumption> due to differing regional definitions and the omission of some modelled site level data that is included on the website but not in the life cycle inventory.

### Thermal Energy

A similar methodology is used to model the impacts of thermal energy input to bauxite mining, alumina production, anode production, paste production and ingot casting.

Graphical user interface, application, Word

Description automatically generated

**Figure 11: GaBi plan for thermal energy modelling from hard coal in the global model**

At the global level, a regional mix was constructed for each energy source (e.g. hard coal), with the percentage share of each region modelled on a relevant proxy LCI dataset (e.g. Brazil for South America) present within the GaBi database (see Figure 11 for an example). The global mix is a production weighted average of the regional models, as for electricity. For each of the scenarios, the region-specific energy carrier mix was modelled for each unit process.

### Classification of Processes and Material Flows

The processes, material inputs and material outputs within the system boundary of the study have been assigned to one of five categories, to understand better the contribution of each to total impacts and to identify the most material influences on impact indicator results for each scenario. The five categories are:

* **Direct process:** Direct, non-fuel combustion inputs and outputs (emissions) associated with primary aluminium production processes (bauxite mining, alumina production, anode/paste production, electrolysis, and casting)
* **Thermal energy:** Material inputs and emissions associated with primary aluminium production thermal energy generation processes, including fuel extraction and preparation (e.g. coal from mine to boiler).
* **Ancillary:** All material and energy inputs and emission outputs associated with non-fuel input materials used in the production of primary aluminium (e.g. production of caustic soda and aluminium fluoride, on-site treatment of solid wastes)
* **Electricity:** All inputs and outputs associated with processes to generate and distribute the electricity directly used in primary aluminium production processes, including fuel extraction and preparation, also transmission losses.
* **Transport:** Inputs and outputs associated with the seaborne, road and rail transport of input materials.

**All inputs and outputs are modelled as elementary flows, i.e. inputs from nature and outputs to nature without human intervention**

### Water Scarcity Footprint

The water scarcity footprint (WSFP) of primary aluminium production is calculated in accordance with ISO 14046. The WSFP of a plant or process quantifies the extent to which the water consumption of the plant or process contributes to water scarcity in the region in which it operates. The cradle-to-gate WSFP, of primary aluminium is determined for the global aluminium industry and four archetype scenarios.

1. **Direct WSFP**, calculated using water consumption data, collected as part of the 2019 LCI survey;
2. **Indirect WSFP**, calculated from data available in GaBi, based on water consumption of the ancillary materials, fuel and electricity needed to produce alumina, anodes, paste and aluminium ingot. The data are identical with the data used for the 2015 LCA report, using AWARE parameters instead of WSI for quantifying the local water scarcity.

To determine the WSFP for each scenario, a site by site approach is adopted for each unit process and each region and then aggregated accordingly, summarised in Table 9. Typically, water data for electrolysis, anode/paste production and ingot casting are reported at a ‘total plant’ level and so the three unit processes are modelled as a single site. Scenario results are summarised in Table 10, using an approach that assumes, for each scenario, an average WSFP of the raw material supplier region, and, considers the amount of raw material required to produce one tonne of product (reference flow).

#### Direct WSFP

Water consumption of the site (input-output) is multiplied by a local characterisation factor to give a site specific WSFP. Available Water Remaining (AWaRe) replaces Water Stress Index (WSI) as the water scarcity characterisation factor in this report. AWaRe is a new consensus method of UN Environment and was developed by the working group on water use in LCA (WULCA), which was released in 2015 and is suggested by JRC as new standard impact assessment method for water use in PEF. The WSFP of all sites in a region are then summed to give a regional WSFP**.** This regional total is then divided by the reporting regional production for a **specific WSFP** per tonne of product.

#### Indirect WSFP

Regionalised quantities of ancillary materials, fuel and electricity consumption for each unit process (available in Appendix A) are multiplied by the characterisation factors for each product (data available in third party databases e.g. GaBi) and summed accordingly. This regional total is then divided by the reporting regional production for a **specific WSFP** per tonne of product.

**x**

**x**

**x**

**x**

**Figure 12: Example WSFP system for direct and indirect WSFP for alumina production**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Region | Bauxite production\* | Bauxite | | Alumina production | Alumina  (exc. Bauxite supply) | | Primary aluminium production | Aluminium  (exc. Alumina supply) | | |
| WSFP | specific WSFP | WSFP | specific WSFP | WSFP | direct specific WSFP | indirect specific WSFP |
| Mt | Mm3 World-Equiv | m3 World-Equiv/t | Mt | Mm3 World-Equiv | m3 World-Equiv/t | Mt | Mm3 World-Equiv | m3 World-Equiv/t | m3 World-Equiv/t |
| Africa | 78 | 29 | 0.38 | <1 | 18 | 49.8 | 1.7 | 3857 | 2.6 | 2256 |
| Asia (ex. China) | 51 | 35 | 0.68 | 11 | 724 | 67.8 | 5.5 | 812 | 50.6 | 98 |
| China | 70 | 75 | 1.07 | 68 | 4306 | 63.6 | 35.8 | 25602 | 8.9 | 706 |
| Europe (EU28 & EFTA) | - | - | - | 4 | 50 | 13.5 | 3.7 | 1549 | 7.3 | 411 |
| Gulf Cooperation Council | 5 | 1 | 0.25 | 3 | 31 | 10.3 | 5.7 | 66 | - | 12 |
| North America | - | - | - | 2 | 96 | 42.2 | 4.0 | 3172 | 1.7 | 801 |
| ...of which Canada | - | - | - | - | - | - | 2.9 | 1568 | 1.5 | 539 |
| Oceania | 106 | 59 | 0.56 | 20 | 725 | 36.3 | 1.9 | 6671 | 1.7 | 3469 |
| Russia and Other Europe | 6 | 6 | 1.07 | 4 | 136 | 30.5 | 4.4 | 2284 | 11.9 | 505 |
| South America | 43 | 13 | 0.30 | 10 | 171 | 17.0 | 1.1 | 222 | 52.8 | 150 |
| Global | **358** | **218** | **0.61** | **124** | **3520** | **28.5** | **63.7** | **45705** | **11.7** | **706** |

\*source: U.S. Geological Survey **Table 9: Regionalised Water Scarcity Footprint (WSFP) per unit process (differences due to rounding)**

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Bauxite | | Alumina | | | | Aluminium | | | | | Mine to Ingot |
| Scenario | A | B | C | D | E | F | G | H | I | J | K | L |
| **Source** | **Specific WSFP** | **Reference flow** | **Specific WSFP**  **(bauxite)**  **= B x C** | **Source** | **Specific WSFP**  **(ex. bauxite)** | **Reference flow** | **Specific WSFP**  **(alumina)**  **= (D + F) x G** | **Source** | **Direct Specific WSFP** | **Indirect Specific WSFP** | **Specific Total WSFP**  **= H + J + K** |
| m3 World-Equiv/t Bauxite | t Bauxite /  t Alumina | m3 World-Equiv/t Alumina | m3 World-Equiv/t Alumina | t Alumina /  t Aluminium | m3 World-Equiv/t Al | m3 World-Equiv/t Al | m3 World-Equiv/t Al | m3 World-Equiv/t Al |
| GLO | *GLO* | 0.61 | 2.7 | 1.6 | *GLO* | 28.5 | 1.9 | 58 | *GLO* | 11.7 | 706 | **775** |
| 1 | *CNA* | 1.07 | 2.7 | 2.9 | *CNA* | 63.6 | 1.9 | 127 | *CNA* | 8.9 | 706 | **842** |
| 2 | *OCA* | 0.56 | 2.8 | 1.5 | *OCA* | 36.3 | 1.9 | 73 | *GCC* | 0 | 12 | **85** |
| 3 | *AFR* | 0.38 | 2.7 | 1.0 | *EUR* | 13.5 | 1.9 | 27 | *EUR* | 7.3 | 411 | **445** |
| 4 | *SAM* | 0.30 | 2.5 | 0.7 | *SAM* | 17.0 | 1.9 | 34 | *CAN* | 52.8 | 150 | **575** |

**Table 10: Water Scarcity Footprint (WSFP) per Scenario (differences due to rounding)**

## Results and Discussion

### Impact Category Indicator Results[[4]](#footnote-5)

The impact category and additional indicator results (including GWP breakdown) have been calculated using GaBi version 2022.2. Water scarcity footprint results are calculated in accordance with ISO 14046. All results are reported per tonne aluminium ingot.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Global | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
| *Bauxite → Alumina → Aluminium* | ***GLO*** | ***CNA→CNA→CNA*** | ***OCA→OCA→GCC*** | ***AFR→EUR→EUR*** | ***SAM→SAM→CAN*** |
| Acidification Potential (AP)  [kg SO2-Equiv.] | 89 | 108 | 44 | 29 | 54 |
| Depletion of fossil energy resources (DFE)  [MJ] | 161,640 | 193,010 | 147,380 | 74,710 | 44,782 |
| Eutrophication Potential (EP)  [kg Phosphate-Equiv.] | 6 | 7 | 4 | 2 | 2 |
| Global Warming Potential (GWP 100 years)  [tonne CO2-Equiv.] | 16.8 | 20.3 | 11.3 | 7.4 | 5.4 |
| Ozone Layer Depletion Potential (ODP)  [kg R11-Equiv.] | 2.6E-9 | 3.4E-9 | 2.8E-9 | 2.6E-9 | 3.6E-9 |
| Photochemical Ozone Creation Potential (POCP) [kg Ethene-Equiv.] | 6 | 8 | 3 | 2 | 3 |
| Water Scarcity Footprint (WSFP - AWARE)  [m3 World-Equiv.] | 775 | 842 | 85 | 445 | 575 |

**Table 11: Impact category and additional indicator results (per tonne of primary aluminium ingot)**

### Contribution Analysis

At the global level an analysis of the relative contribution of the process categories highlights the significant influence that (the globalised aluminium) electricity supply has on the potential environmental impact of primary aluminium production (Figure 13). Electricity consumed in global primary aluminium production contributes between 50% and 90% of the environmental impact across most impact categories considered in this study. The only exception is Ozone Layer Depletion Potential.

**Figure 13: Contribution of key process types to global impact indicator category results**

A similar analysis of process contribution across the four example scenarios is presented in Figure 14, showing significant differences between them. Generally, the scenarios with a greater proportion of thermal power consumption have electricity as the most significant influence on the impact category indicator results. The scenarios which are hydropower dominated on the other hand have a greater contribution from direct, thermal and ancillary processes and materials.

Contribution analysis is useful in identifying hotspots or key process contributors and as such assists practitioners in identifying inventory flows which are of most importance. Conversely, inventory flows which are now less significant contributors and can be reviewed as needed for the next phase of data collection.

Thermal Energy

Direct Process

Ancillary Materials

Transport

Electricity

**Figure 14:Relative contribution of each process type to impact category indicator results by scenario**

### Relative Contribution of Aluminium Production Unit Processes to GHG emissions

The most significant greenhouse gas contributions at the global level are attributable to alumina production and electrolysis unit processes. The magnitude of greenhouse gas emissions is a function of thermal energy fuel mix and power mix. The following analysis is based on a GaBi model populated with the relevant thermal energy carrier and electricity mix data reported to the IAI as part of its annual energy surveys (with consumption data from the LCI). Beyond this direct industry data, default background data and assumptions within GaBi were used uncritically.

**Figure 15: Global GHG emissions by unit process and process type**

Results for the archetype scenarios are shown in Figure 16. Direct, ancillary and transport related emissions are similar across scenarios, as there is only minor variation between technologies and regions. The relative contribution of each process type differs depending on the total GHG emissions and therefore the significance of each process type is dependent on the specific scenario being modelled. The largest differences between the scenarios are associated with electricity supply and, to a lesser extent, thermal energy.

**Figure 16: GHG emissions by scenario and by process**

Scenario 1: CNA-CNA-CAN

Scenario 2: OCA-OCA-GCC

Scenario 3: AFR-EUR-EUR

Scenario 4: SAM-SAM-CAN

## Interpretation and Conclusions

### Significant Issues

The results presented in this study show that the impacts associated with the production of electricity remain the most significant contributor to overall environmental impact of primary aluminium production at a global level; over 50% across most impact category results.

The differential impact of energy sources is demonstrated in the example scenarios, which illustrate that aluminium production based on coal-fired electricity has a higher potential environmental impact compared to primary aluminium production based on hydropower or gas.

Electricity emissions, contributing around 65% to GHG emissions, are the most significant contributors at the global level. This is in line with the findings of previous analyse for 2015. Followed by direct process emissions as the 2nd most significant, contributing 14%. Electricity and direct process emissions are also the most significant contributors in three of the four example scenarios. Scenario 4, where hydropower electricity dominates, is the exception to this; the main contributors are process emissions (44%) and thermal energy (25%).

The share of coal and oil consumed by the production of both alumina and aluminium has decreased over the past decade[[5]](#footnote-6). Also, the use of best available smelting technologies in the new capacity, paired with the closure of older, less efficient facilities has reduced process energy intensity[[6]](#footnote-7).

### Limitations

**Data quality:** as reported in Chapter 2, all reported data points were checked individually using a systematic approach. Significant variations (+/- 2STD) in reported data, or +/- 15% when compared with 2015 data and without obvious reason (e.g. production change), were queried with reporters and either confirmed or amended as appropriate. Survey data quality is also dependent on the interpretation of the reporter on the scope of the data point being surveyed. IAI includes detailed notes in the LCI survey sent to reporters about data points that are open to greater interpretation to encourage consistent reporting of data.

**Reporting rates:** reporting rates for the life cycle inventory survey are discussed in Chapter 2. Reporting rates for individual data points vary and, for some, the inventory averages represent a very small percentage of the global or regional production and so are accompanied by a high level of uncertainty. Reporting rates are published with each data point in Appendix A to inform users on the representativeness of the inventory data. Overall, reporting rates have been improved since 2015. However, the data representativeness could be better if there is greater coverage of newer and emergent regions of production such as China and Other Asia.

**Modelling and Background Data:** With regards to modelling in the GaBi database, there are inevitably some limitations to the accuracy of the results given that the quality of background dataset can vary considerably. In addition, proxy datasets have been used when the required datasets were not available. IAI recognises that limitations associated with the model and the robustness of background data have significant implications for the impact indicator results in this study.

### Conclusions and Next Steps

Overall, the results from this study validate previous findings.

The global industry, through the Institute will continue to ensure that up to date, robust inventory and power mix data is available for use by LCA practitioners. Life cycle inventory data is updated at five-year intervals and as such, the next update will likely be published in 2027 representing data for the year 2025.

The data, methods and analysis included in this study have been subject to ongoing, independent third-party review. The review panel have provided feedback at key stages in the study and have greatly improved the study as a result. A summary report by the review panel is attached as Appendix E to this report. Highlights include data used in the foreground are solid, quality checked, reasonable and as complete as possible; the inventory analysis methods applied are consistent with the ISO standards; the derivation of average unit processes from raw data and information, and the inventory models are scientifically and technically valid. It is recommended to address toxicity and land use in future update of the LCI data of the aluminium supply chain. Also, it is recommended to continue increasing the data coverage, as well as regional impact assessment. The change of method for Water Scarcity Footprint assessment, from WSI to AWARE, does not allow results comparison between 2015 and 2019 – although AWARE method is recommended by the Life Cycle Initiative of UN Environment.

The iterative nature of life cycle assessment means that the results of this study should be reviewed prior to the next iteration so that inventory flows which are now less significant contributors to environmental impacts can be replaced by those which are of greater significance. Again, it is important to acknowledge that the materiality of inventory flows is dependent on the exact scenario being modelled and so the results of contribution analyses will vary. At the global level, however, it is clear that further work should be undertaken with regards to background data The Institute’s long term objective is for such nuanced data to be made available for use by practitioners, allowing more accurate calculation of potential impacts across space and through time.

The inventory datasets published as part of this study, are the most accurate and up-to-date of any available LCI on primary aluminium production. They should be used by life cycle practitioners in LCAs of aluminium containing products where specific supply-chain data is not available. The 2019 dataset for the first time includes regionalised mining data, unit process level data. This should better equip LCA practitioners and allow for aluminium product LCAs that are more representative of material produced in specific regions and reflect changes in production centres over time.

It is clear to see that the primary aluminium industry landscape has changed significantly over the past decade; the location of primary aluminium smelters, and consequently, the industry’s power mix have shifted. With this, the potential environmental impacts associated with the generation of electricity for the electrolysis process plays an increasingly important role at the global level. This study, with the publication of industry specific, regionalised smelting power mixes and regionalised foreground LCI data, demonstrates the industry’s ongoing commitment to understand better the potential environmental impacts associated with its processes and products on a global and regional level, to make available any relevant data and to support wider life cycle practices.

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1. Care should be exercised when using air emissions data in this report, namely SO2 and NOx emissions. Reported facility data on air emissions include those associated with fuel combustion. It is recommended that life cycle practitioners be aware of the potential for double counting of such emissions. [↑](#footnote-ref-2)
2. & 3 2019, instead of 2020, LCI was collected to exclude the pandemic impact on normal operation. [↑](#footnote-ref-3)
3. [↑](#footnote-ref-4)
4. The results of this study are **not intended to be used in comparative assertions** and are an ***example*** of how the inventory data can be used in life cycle assessments. [↑](#footnote-ref-5)
5. <http://international-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/>

   https://international-aluminium.org/statistics/metallurgical-alumina-refining-fuel-consumption/ [↑](#footnote-ref-6)
6. <http://international-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/>

   https://international-aluminium.org/statistics/metallurgical-alumina-refining-energy-intensity/ [↑](#footnote-ref-7)