



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

2015 DATA

FINAL

June 2017

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1. 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 and 2010. 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.

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, from mining of bauxite ore to ingot manufacture, including: raw material inputs, energy use, emissions to air and water and solid waste generation. The Institute believes that up to date, robust inventory data should be made available for use by LCA practitioners to complete independent impact assessments. In addition to providing such data, this report will also demonstrate 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.

This report and accompanying data demonstrates 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, 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. The Institute has provided regionalised LCI datasets for the first time, to ensure that users have access to more specific data for analyses related to regional markets or for the modelling of specific inter-regional flows.

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

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.

2. Life Cycle Inventory (LCI)

2.1. Goal and Scope

The goal of the 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. The full inventory is available in Appendix A. The regions are outlined in Table 1.

Region Name	Region Code
Global	GLO
Africa	AFR
Asia ex China	OAS
Canada	CAN
China	CNA
Europe (EU28 & EFTA)	EUR
Gulf Cooperation Council	GCC
North America	NAM
Oceania	OCA
Russia and Other Europe	ROE
South America	SAM

Table 1: IAI LCI Regions 2015

This inventory provides production weighted mean data that may also be used as benchmarks for individual companies to determine significant environmental aspects within their own processes.

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 is cast into ingots, the usual form suitable for further fabrication of semi-finished aluminium products.

Background processes are specified in the flow diagram in Appendix A. These processes are outside of the scope of this LCI, but they have the potential to contribute much greater environmental impact than the unit processes within it. Such additional unit processes (in particular supply of fuel and electricity, and production of ancillary raw materials such as petrol coke, pitch and caustic soda) are not 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 Chapter 3 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 <http://www.world-aluminium.org/statistics/primary-aluminium-smelting-power-consumption>.

Year 2015 data (regionalised according to this report, rather than IAI's online published energy regions – see Section 2 below) are replicated in Table 2, with a historical perspective (1980-2015) on global power mix illustrated in Figure 1.

% power mix	Africa (AFR)	Asia (ex China) (OAS)	Canada (CAN)	China (CNA)	Europe (EUR)	GCC (GCC)	North America (NAM)	Oceania (OCA)	Russia & Other Europe (ROE)	South America (SAM)	World (GLO)
Hydro	57	14	100	10	68	0	74	27	98	72	30
Coal	43	86	0	90	10	0	24	73	2	0	59
Oil	0	0	0	0	1	0	0	0	0	0	0
Natural Gas	0	0	0	0	5	100	1	0	0	27	9
Nuclear	0	0	0	0	16	0	1	0	0	0	2
Total	100	100	100	100	100	100	100	100	100	100	100

Table 2: Year 2015 aluminium industry power mix data

¹ Care should be exercised when using air emissions data in this report, namely SO₂ and NO_x 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. Estimates for greenhouse gas emissions related to fuel combustion are included for reference and have been calculated based on the GHG protocol tools (World Resources Institute, 2015).

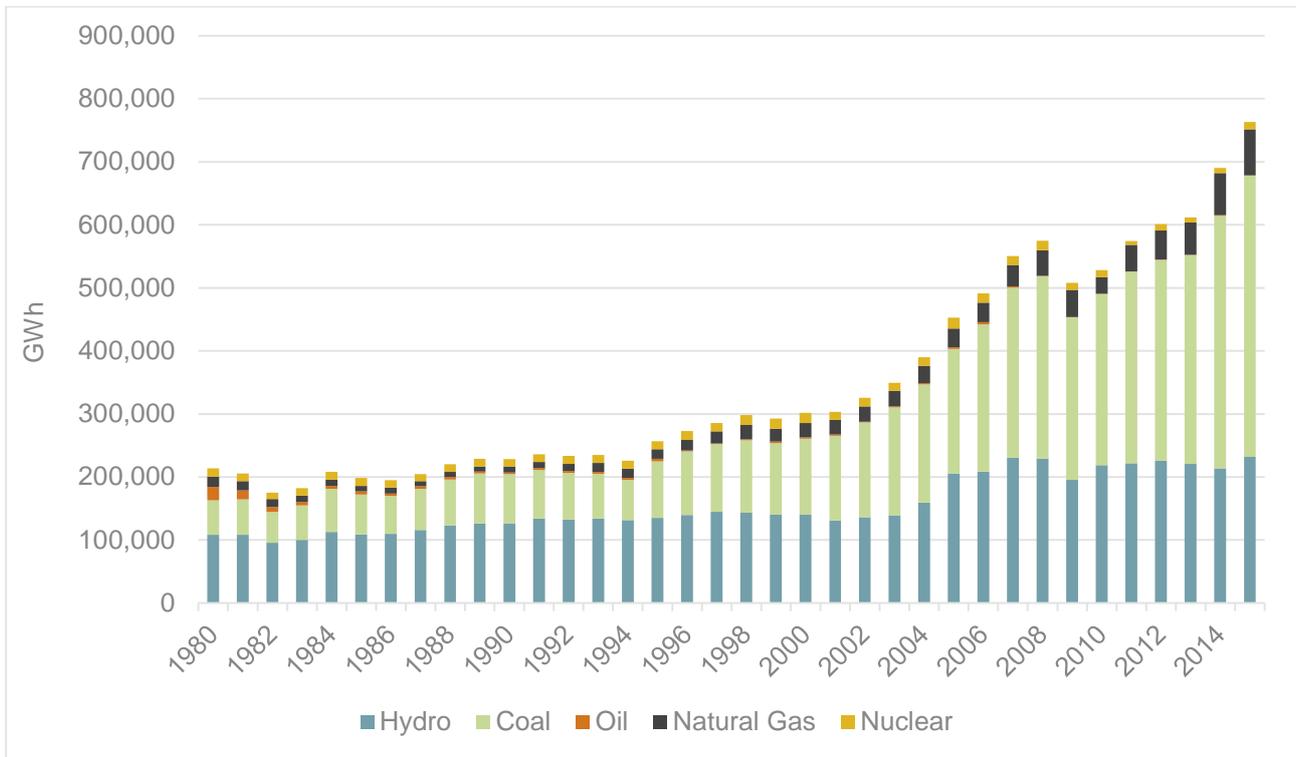


Figure 1: Global aluminium industry power mix for years 1980 – 2015

Fuel consumption data (kg hard coal, diesel oil, heavy oil; m³ natural gas) and the direct carbon dioxide emissions associated with their combustion 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 kWh electricity, relevant power mix and appropriate background data from alternative databases as demonstrated in Chapter 3.

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

2.2. Data Selection

This report contains data for the calendar year 2015. Data for 2010 are also included for select sites that did not report data for the year 2015 but are still in operation. Data reported as part of the 2010 LCI survey are used as a proxy for sites where the process is unlikely to have changed significantly, but applied to the 2015 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.

2.3. *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 (1,120 kg) than the corresponding electrolysis metal input (968 kg), due to a “cold metal” contribution from remelt (100 kg remelt ingot) and recycled (29 kg external scrap) aluminium. This cold metal contribution is excluded by adjusting all inputs and outputs from the survey average by a factor of 0.89, calculated as follows:

$$\text{(electrolysis metal + alloy additives)} / \text{(total metal input – scrap output sold)}$$

$$(988 \text{ kg}) / (1,120 \text{ kg} - 7 \text{ kg}) = 0.89$$

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 0.89.

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, 2013; European Aluminium Association, 2013).

2.4. *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 5,540 kg. This typically includes a significant water component of around 10-20% (c.600-1,000 kg). Part of the bauxite ore is deposited as bauxite residue (2,373 kg) or recycled (57 kg). The mass of material output from the alumina production process is thus around 2,000-2,500 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.



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 net anode consumption (460 kg) is higher than the theoretical mass predicted by stoichiometric analysis (333 kg).

2.5. 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 (including electricity mix)
- PFC emissions

Unfortunately, data of sufficient quality are not available for other LCI flows from the Chinese aluminium industry, which represented around 55% of global production in 2015. The geographical survey coverage is discussed further in Section 2.

2.6. Data Collection

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

- 2015 Life Cycle Survey (5-yearly) covered all required LCI data except those already collected through established, annual IAI surveys;
- 2015 Bauxite Residue Survey (5-yearly) gathered data on the production, storage and reuse of bauxite residue;
- 2015 Energy Survey (annual) of alumina production, electrolysis, anode production and casting processes;
- 2015 Anode Effect Survey (annual) used to calculate perfluorocarbon emissions estimates from the electrolytic process.

Survey forms (Appendix C) were sent out to reporters in Q1 2016 requesting data for the 2015 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 2010 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 2010) 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.

In a few select cases, regional associations (e.g. *European Aluminium*) provided data collected from their members to supplement the IAI's LCI data collection process. Such input was important to ensure alignment of key input and output flows at the regional level.



2.7. Survey Coverage

Figure 2 illustrates the coverage of LCI and Energy Survey data for 2015 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 51% and 55% of the world's 2015 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.world-aluminium.org/statistics>) and included in Table 2 and Figure 1.

In addition, data on PFC emissions directly measured at a sample of Chinese smelters between 2008 and 2012, forms the basis of assumptions of Chinese emissions performance, as reported in the IAI's annual Anode Effect Survey Reports (<http://www.world-aluminium.org/publications/tagged/PFC/>).

The inclusion of such aggregated data and estimates results in an improvement on the 2010 reporting coverage for a number of key data points.

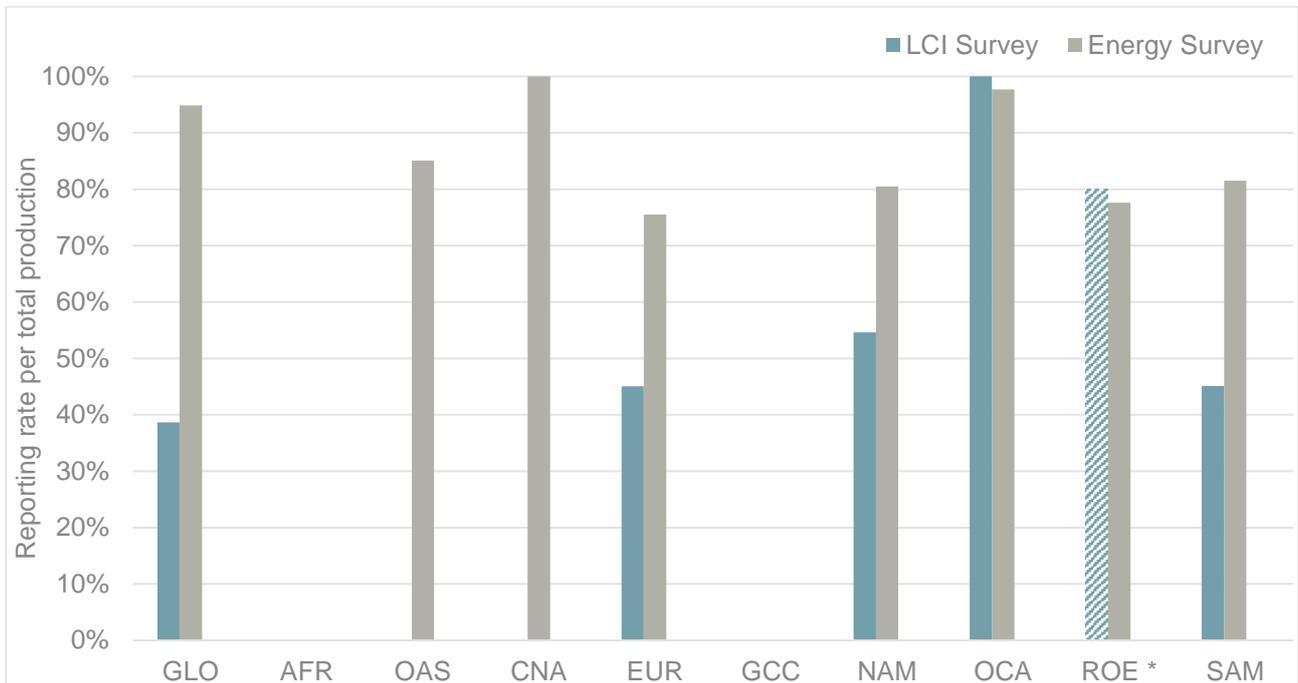


Figure 2: Response rates LCI (Alumina) and Alumina Energy 2015 by region

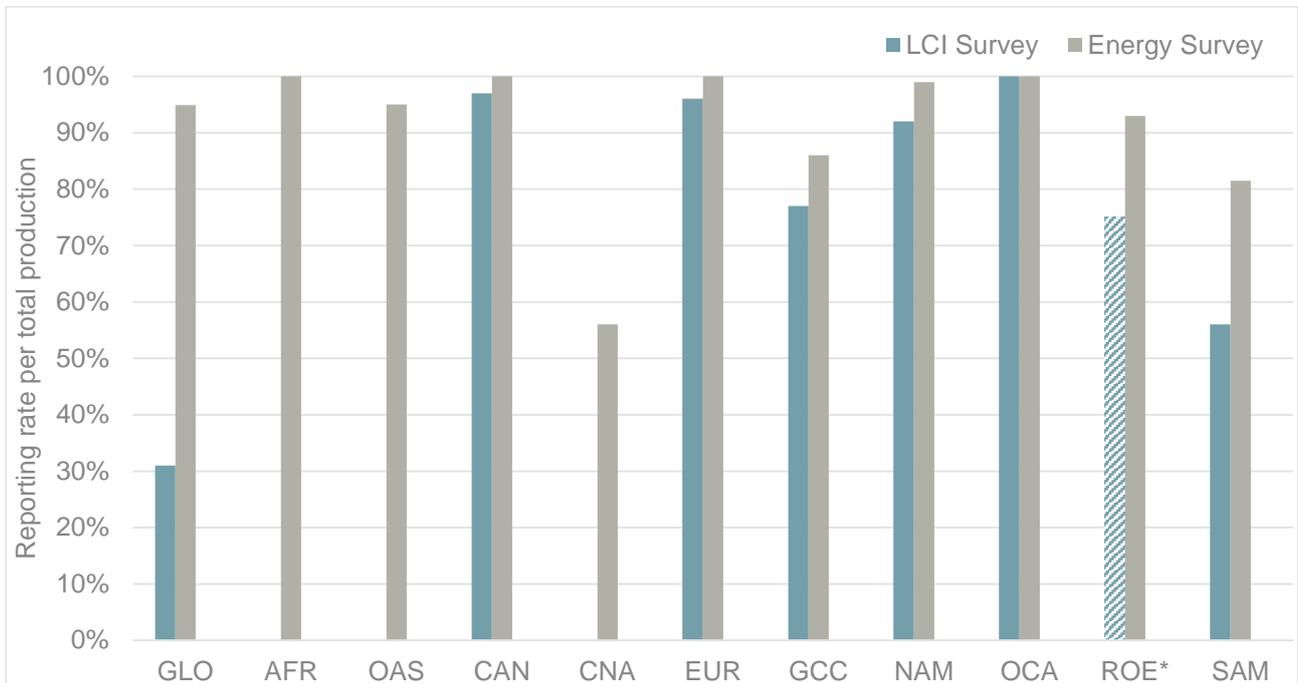


Figure 3: Response rates LCI (Electrolysis) and Electrolysis Energy 2015 by region

[* Russia and Other Europe (ROE) – reporting coverage is estimated as multi-region, company level data was reported. This limited regional data disaggregation so company level data is included in GLO only.]

2.8. 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 2015. 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 *Söderberg*. Around 16% of the total aluminium production covered by LCI survey reporting was produced using *Söderberg* technologies, with the remaining 84% from *Prebake* facilities. This is not reflective of the global technology split which is 95% *Prebake* and 5% *Söderberg*; Chinese facilities only employ *Prebake* technologies.

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

2.9. Assumptions for Non-Reporting Production

Assumptions for non-reporting production are made for facilities that did not report in 2015 but are still in operation and reported in 2010. The reported data for these facilities was included on a per tonne of production basis applied to 2015 production levels. Assumptions for non-reporting production were also made with relation to China for anode consumption, energy input and PFC emissions, as noted above. For the other data averages included in the inventory, no assumptions are made for non-reporters. Data in the combined Summary inventory in Appendix A (per tonne of primary aluminium ingot) however, is calculated based on the year 2015 global production weighted technology split between *Prebake* (95%) and *Söderberg* (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.

2.10. Data Analysis

2.10.1. 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.

2.10.2. Averaging

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

2.10.2.1. 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	4.88

Table 3: Example data for explanation of Weighted Mean

$$\begin{aligned}
 \text{Weighted Mean} &= \text{SUM}(C2:C7)/\text{SUMIF}(C2:C7, "<>" \&"" , B2:B7) \\
 \text{(using Microsoft Excel function syntax)} &= (132)/(10+20+25+300) \\
 &= 132/355 = \mathbf{0.37 \text{ kg/t}}
 \end{aligned}$$

2.10.2.2. 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

$0.37 * 5.6 = \mathbf{2.07 \text{ kg}}$ bauxite related emissions per tonne of aluminium produced

2.11. *Changes in Inventory Data from 2010 to 2015*

Changes (or lack thereof) in inventory data between the 2010 and 2015 datasets can be broadly accounted for by one or both of 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 2010 and 2015 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.

2.11.1. *Bauxite Mining*

2.11.1.1. Data Driven Differences

Sea water input and output is zero compared to 4 m³/t Al ingot in 2010. Only one facility reported sea water input and output in the 2010 survey. However, for the 2015 survey, the facility reported that it no longer had sea water input or output. Only mines that are located at the coast have the potential to use sea water for washing bauxite. Sea water input and output are of minor environmental relevance.

Fuels and electricity consumption are different from 2010, with an increase in heavy fuel oil input and a decrease in electricity input. These changes are a consequence of increased reporting coverage for heavy fuel oil and improved reporting practices from sites with respect to electricity input e.g. reporters were able to allocate energy input more easily by unit process and as such the data for the bauxite mining unit process had changed. It should be noted that energy consumption is very small in the mining process compared to subsequent thermal and electrochemical unit processes.

Land transformation and **land occupation** related to bauxite mining have been included for the first time in the 2015 inventory as a result of suggestions made in the previous third party review (IAI 2013).

2.11.1.2. Performance Driven Differences

Particulate air emissions appear to be down by 43%. The 2015 data can be considered more reliable as the reporting cohort accounts for a greater percentage of global production than 2010. A large bauxite mine that reported in 2010 and in 2015 also had a significant decrease in particulate air emissions per tonne of product over this period, as a result of improved dust management practices, contributing to a lower overall average.

Mine solid waste has increased since 2010 as a result of a change in waste disposal at a major bauxite mine. Previously, waste was used onsite in another part of the operation but this has stopped recently and the 2015 data reflect an increased amount of industrial waste being sent offsite for treatment prior to disposal.

2.11.2. Alumina Production

2.11.2.1. Data Driven Differences

Inventory Flow	Unit	2010	2010 (Revised)	2015
Sulfur Dioxide Emissions	kg/t Al ingot	4.7	2.2	2.2
Suspended Solids Emissions	kg/t Al ingot	0.03	2.0	0.08
Mercury Water Emissions	g/t Al ingot	0.0001	0.003	0.0009
Oil and grease/ total hydrocarbons	kg/t Al ingot	1.5	n/a	3.2

Table 4: Life cycle inventory alumina data differences for year 2010 and 2015

Sulfur dioxide emissions appear to have decreased by 53% since 2010. The sulfur dioxide emissions at a number of major refineries remained relatively stable from 2010 to 2015. The apparent reduction in the 2015 average is attributable to an anomalously high data point being included in the 2010 average. The reporting coverage for 2015 is higher than 2010 and so can be considered the most reliable figure.

Suspended solids appear to have increased between 2010 and 2015. The 2010 average was erroneously low due to a unit conversion issue. Sites reported data in tonnes but the inventory flow was in kilograms per tonne. If the error is corrected, the 2010 value is actually higher (2.0 kg/t Al) than the 2015 average (0.08 kg/t Al) showing a reduction in emissions.

Mercury water emissions appear to have increased between 2010 and 2015, but the 2010 average was erroneously low due to a unit conversion issue. Sites reported data in kilograms but the inventory flow was in grams per tonne. Additionally, the 2010 average included an anomalously high data point for a significant alumina producer. If the errors are corrected, the 2010 value is actually higher (0.003 g/t Al) than the 2015 average (0.0009 g/t Al) showing a reduction in emissions.

Oil and grease/total hydrocarbons has increased since 2010 with the increase in reporting coverage. The 2015 average can be considered more reliable as it accounts for a greater reporting percentage.

Land transformation and **land occupation** related to bauxite residue storage have been included for the first time in the 2015 inventory as a result of suggestions made in the previous third party review (IAI 2013).

Particulate emissions have decreased as a result of the closure of a large alumina refinery which reported high levels of particulate emissions in 2010. Overall, particulate emission levels have remained relatively stable at a number of sites since 2010.

Fuel mix

Differences in fuel mix between 2010 and 2015 data are summarised in Table 5. The data indicate a shift from oil to coal. However, data from China, where coal dominates the fuel mix (>70 % on a GJ/t Al₂O₃ basis), are not included the 2010 dataset; hence the increase in coal and electricity input for the 2015 global average.

Fuel Type	Unit	2010	2015
Heavy oil	kg/t Al ₂ O ₃	83	25
Diesel oil	kg/t Al ₂ O ₃	0.1	1
Natural Gas	m ³ /t Al ₂ O ₃	139	68
Coal	kg/t Al ₂ O ₃	74	295
Electricity	kWh/t Al ₂ O ₃	79	218

Table 5: Life cycle inventory alumina fuel mix data for years 2010 (ex. China) and 2015 (inc. China)

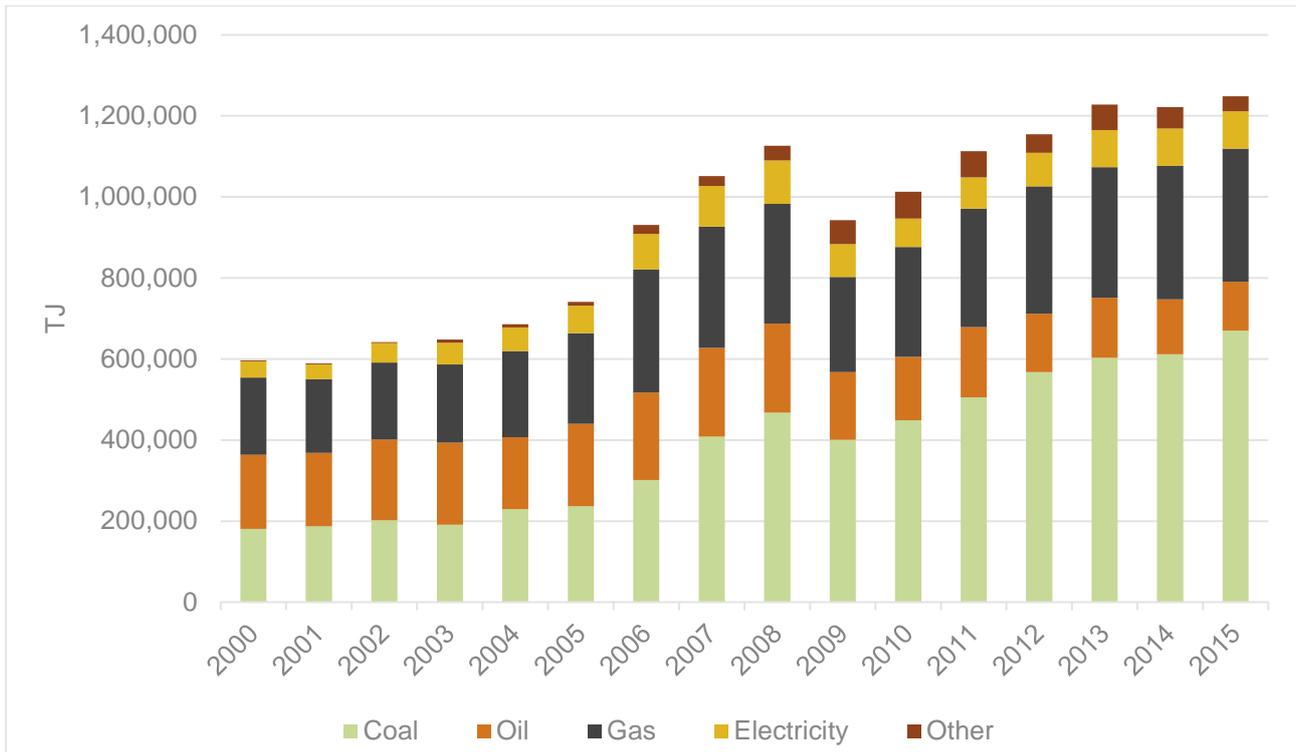


Figure 4: Global alumina industry fuel mix for years 2000 – 2015

Comparing the global alumina (including China) industry fuel mix from 2010 to 2015, energy intensity of the process has actually decreased from 14,000 MJ/t Al₂O₃ to 12,000 MJ/t Al₂O₃. This is not a reporting difference and represents a real change in the industry’s energy consumption per tonne of product. Technological efficiency improvements in newly installed capacity is the main driver of the improvement, but the use of sweetening processes in China to improve feed-stock quality and boost yield, also lowers the overall energy consumption per tonne.

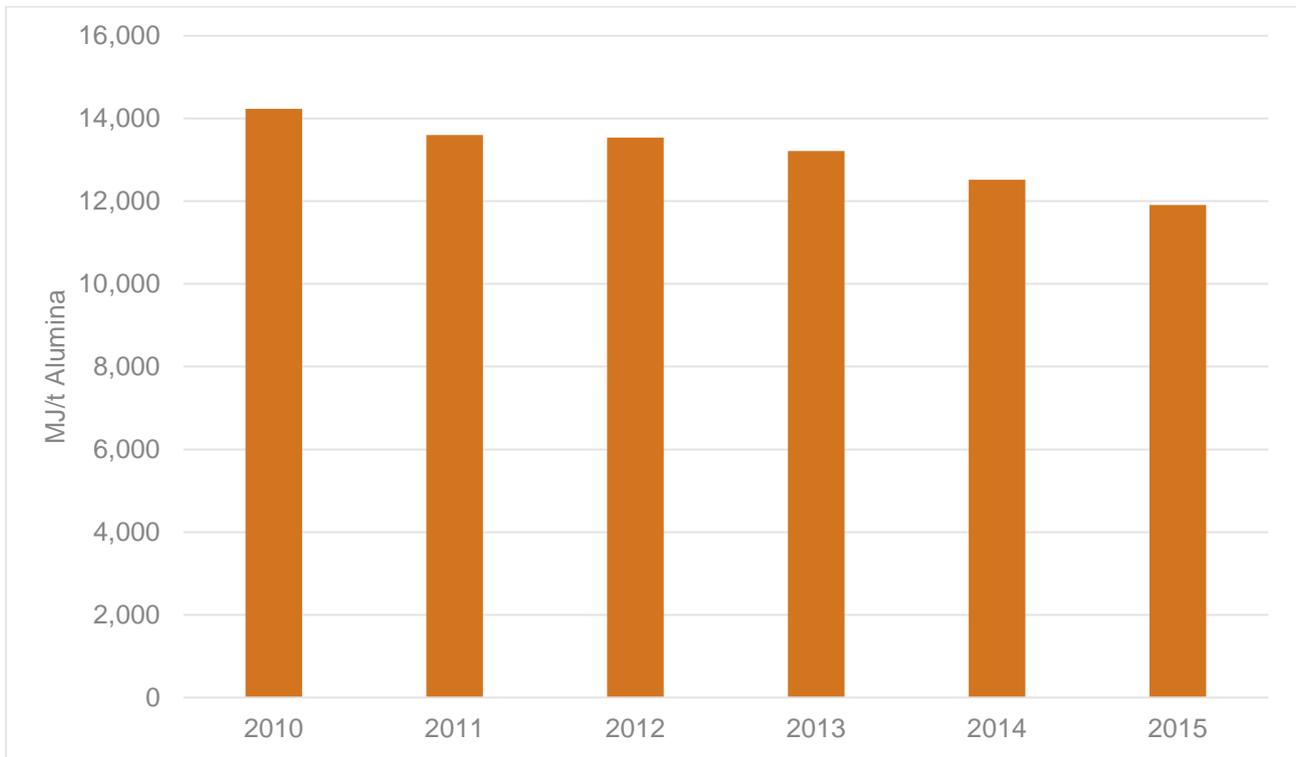


Figure 5: Global energy intensity of the alumina production process for years 2010 – 2015

2.11.2.1. Performance Driven Differences

Calcined lime consumption decreased, reflecting a real process change with a number of sites from 2010 reporting lower consumption in 2015.

Bauxite residue recycled increased by over three orders of magnitude between 2010 and 2015 as a result of increased use of bauxite residue in commercial applications (e.g. cement production, refractories and landfill covering). It should be noted that bauxite residue recycling is often a cyclical process and therefore annual recycling rates can vary. The 2015 bauxite residue survey results also indicate that some refineries reuse bauxite residue onsite as a construction material, although this is out of the scope of the LCI. Research into bauxite residue utilisation is ongoing. Further details on bauxite residue production, utilisation and storage are available in the IAI's Bauxite Residue Survey Results Report. Bauxite residue recycling accounts for approximately 2% of the total residue that is produced, so although there has been a large percentage increase, the volumes involved are still relatively small.

2.11.3. Anode Production, Electrolysis & Ingot Casting

2.11.3.1. Data Driven Differences

Electricity consumption has decreased from 15,275 kWh/t Al in 2010 to 14,214 kWh/t Al in 2015, reflecting the inclusion of new, high efficiency Chinese capacity in the dataset. The majority of new production capacity installed over this period is located in China, where energy constraints and increasing regulatory pressures have led to improvements in energy efficiency and adoption of best available technology across the industry. Inclusion of China in the 2010 dataset would bring the global average for that year down to 14,777 kWh/t. This indicates that electrical energy intensity has been reduced over the 2010 to 2015 period.

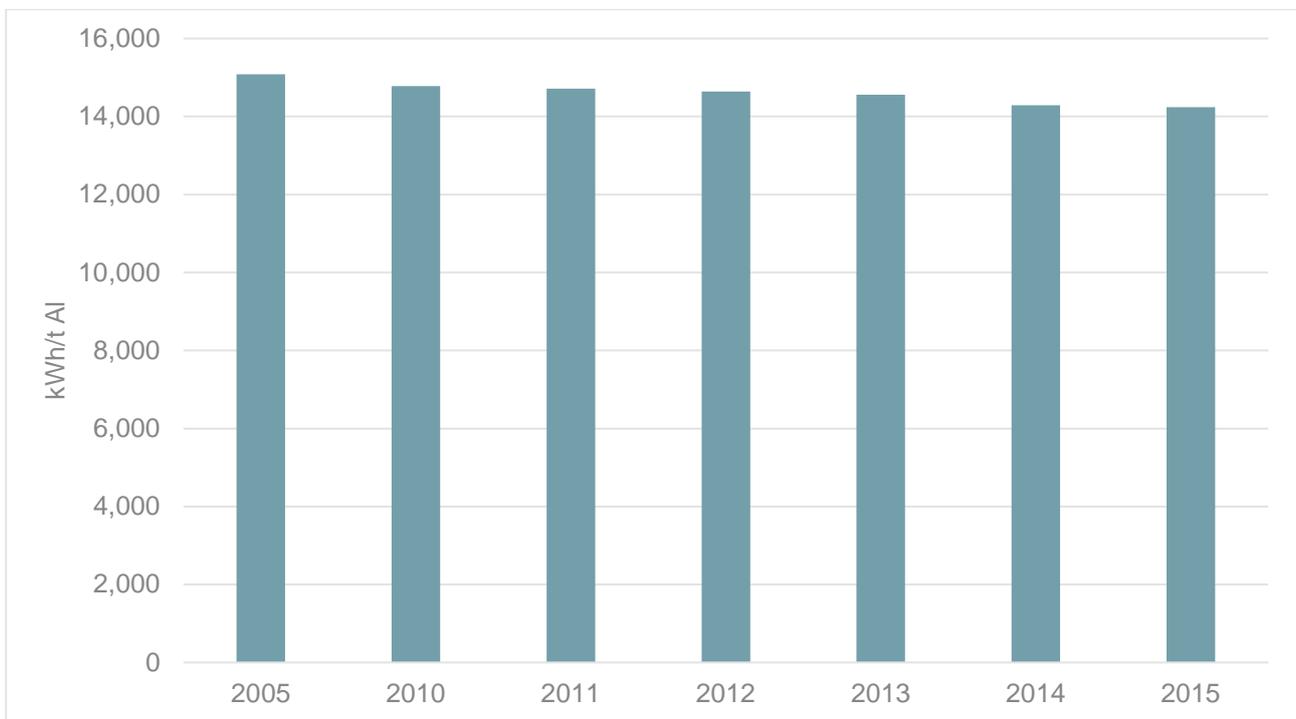


Figure 6: Global aluminium smelting electrical energy intensity for years 2005 – 2015

Freshwater consumption (input-output) has increased from 0.5 m³ H₂O/t Al in 2010 to 0.9 m³ H₂O/t Al in 2015. **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.

Sea water input and **output** has increased since 2010 as a result of the new capacity in the Arabian Gulf, where seawater is used in cooling and wet scrubbing processes, undertaken at a number of smelters. Wet scrubbing involves diluting smelter air emissions, which are included in the inventory, into sea water to harmless concentrations.

Fluoride emissions to air from anode production appear to have increased because of a unit error reporting issue with one of the sites included in the 2010 dataset. Correcting for the unit error issue (0.005 kg/tonne for particulate fluorides and 0.015 kg/tonne gaseous fluorides), fluoride emissions to air from anode production have been reduced in 2015 (0.003 kg/tonne particulate fluorides and 0.007 kg/tonne gaseous fluorides).

The 2015 response rate for **polycyclic aromatic hydrocarbon** and **fluoride** emissions to water for anode production was very low (2% global production), and as such the 2010 data is considered more reliable and should be used as appropriate. The 2010 data are included in the 2015 inventory.

Emissions of the perfluorocarbon (PFC) gas **tetrafluoromethane** (CF₄) appear to have increased by 32%, mainly due to the inclusion of Chinese production, for which an estimated average emission level (higher than the average of non-China prebake technologies) has remained unchanged since 2013. The difference in PFC emissions signature from Chinese smelters (a function of the impact of higher low voltage anode effects compared to the rest of the world) and their inclusion in the 2015 dataset has also led to an apparent decrease in the global average for **hexafluoroethane emissions** (C₂F₆) compared to 2010. The ratio of Chinese C₂F₆ to CF₄ emissions by weight is 0.05 compared with 0.09 for the rest of the world. It should be noted that PFC emissions (and subsequent CO₂ eq. of the two gases) from the aluminium industry have been reduced significantly over the past two decades through improved cell management systems and practices (Figure 7). Further information on perfluorocarbon emissions accounting can be found in the IAI’s annual Anode Effect Survey Reports (<http://www.world-aluminium.org/publications/tagged/PFC/>)

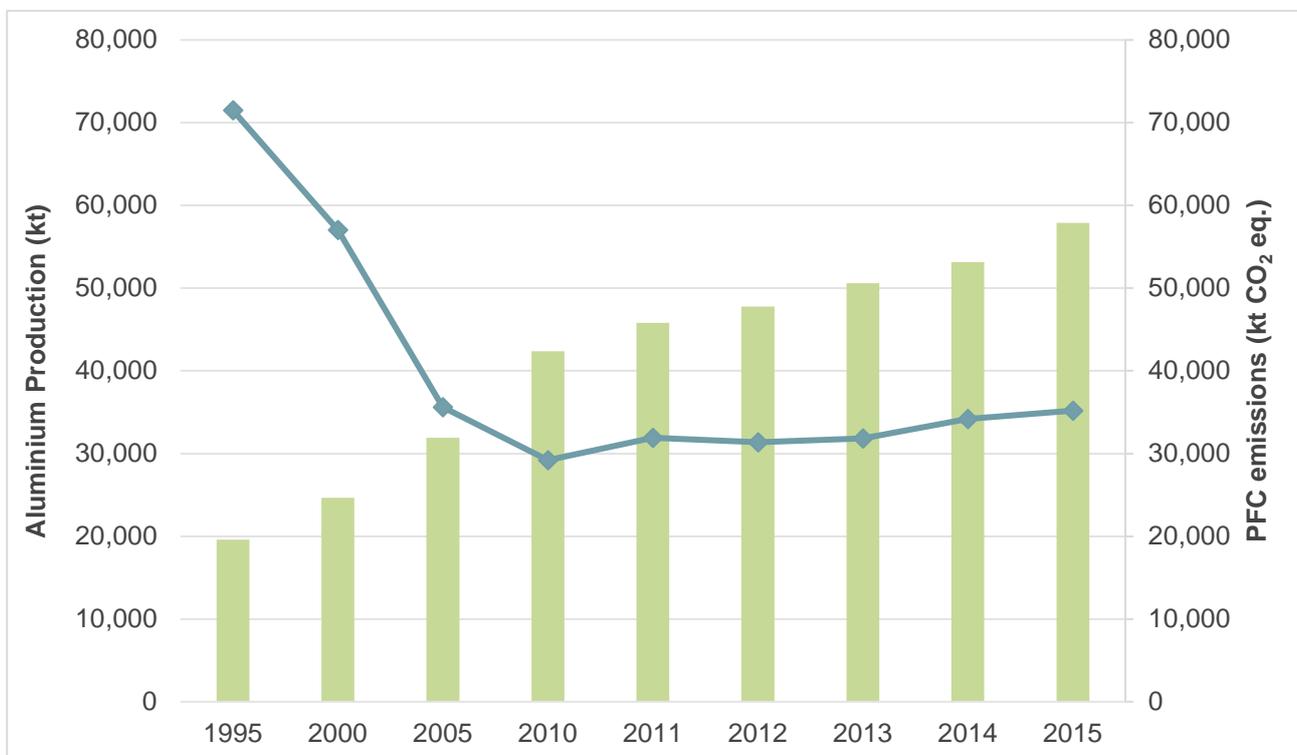


Figure 7: Total global aluminium industry perfluorocarbon emissions against global production

2.11.3.1. Performance Driven Differences

Inventory Flow - Electrolysis	Unit	2010	2015
Total polycyclic aromatic hydrocarbon emissions to air	kg/t Al ingot	0.05	0.02
Particulate Fluorides to air	kg/t Al ingot	0.5	0.2
Gaseous Fluorides to air	kg/t Al ingot	0.6	0.4

Table 6: Life cycle inventory aluminium data differences for year 2010 and 2015

Polycyclic aromatic hydrocarbon emissions to air (including benzo-a-pyrene) from the electrolysis process have decreased since 2010. This is partly the result of continued improvement in emissions management at smelters as well as a shift in the technology mix towards Prebake smelters.

Fluoride emissions to air from electrolysis have decreased from both Söderberg and Prebake technologies through the use of improved fume control systems, operational good practice and best available technology. Closure of older, high emission Söderberg capacity has also lowered the overall global emissions average.

Particulate emissions have decreased as a result of the closure of a number of smelters which reported high levels of particulate emissions in 2010. Overall, particulate emission levels have remained relatively stable or decreased slightly at most sites since 2010 resulting in a lower particulate emissions average for 2015.

2.12. 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 2015 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 land occupation and transformation for the bauxite mining and alumina production unit processes, the coverage of relevant inputs/outputs can be seen to have improved on the 2010 inventory.

The data, methods and interpretation of this LCI have been subject to ongoing, independent, third party review by a panel of three internationally recognised life cycle assessment experts: Rolf Frischknecht, Walter Klöpffer and Kurt Buxmann.

As a result of the interim reviews and teleconferences conducted during the analysis, a number of improvements have been made to the final published inventory:

1. The method for data averaging has been simplified to avoid confusion between different types of averages; in this report, production weighted average is only reported, whereas in previous years an 'industry average' has also been reported for certain values.
2. The presentation of water data as "water consumption" (the net of input and output values) as this is the data that are required to model life cycle impacts related to water use.

Feedback from the reviewers has also revealed areas for potential improvement, which will be considered in future iterations of the inventory:

- Increased coverage of the Chinese aluminium industry data;
- 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; and
- A review of changing auxiliary or background processes (e.g. consumption of desalinated seawater)

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 2010 LCI, signalling an improvement in the overall quality and representativeness of the 2015 dataset compared to previous years. Additionally, although Chinese LCI data is lacking for a number of inventory flows, the 2015 dataset has greatly improved coverage for energy input (fuel combustion and electricity consumption/power mix) and anode consumption as a result of aggregated data reported by the China Nonferrous Metals Industry Association (CNIA).

Significant differences in aluminium industry smelting process input-output data tend to be a function of technology in use rather than location. 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 (IAI 2014), 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. The importance of industry specific power mixes will be explored in the following chapter as part of the Life Cycle Impact Assessment.

3. Life Cycle Impact Assessment (LCIA)

3.1. Goal and Scope

The **goal** of the Life Cycle Impact Assessment (LCIA) phase is to evaluate potential environmental and human impacts of resource uses and releases 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.

The results of this study are **not intended to be used in comparative assertions** and are an *example* of how the data generated as part of the inventory phase can be used in life cycle assessments. Life cycle practitioners should use 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 2015 inter-regional flows of bauxite to alumina to aluminium, where possible. For the 2014 Environmental Metrics report, two distinct datasets were modelled in GaBi, one *Global* and one for the *Rest of World* (Global minus China). In recent years, the need for increasingly specific data has led IAI to develop 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 differential energy sources). As a result, the impact assessment phase of this LCA utilises the new regional datasets, as well as regionalised power mixes and, where available, regionalised background data (e.g. Europe, Canada), and provides *example* scenarios of primary aluminium production from mine to casthouse.

The study has undergone an interactive **independent third-party critical review** by a panel of life cycle experts (Rolf Frischknecht, Walter Klöpffer and Kurt Buxmann) to ensure the methods, data and interpretations of this study are reasonable, consistent and valid.

3.2. Methodology

3.2.1. Selection and Definition of Impact Categories

The impact categories included in this study are aligned with previously published primary aluminium industry data (IAI 2014) 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 (Buxmann 2016), in light of increasing awareness around water use impacts across the resource sector.

A breakdown of the relative contribution to global warming potential 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 for the first time. Land use impacts, as recommended by the independent third-party review panel, will be considered for inclusion in subsequent reports. 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 (PE International 2014). The aluminium industry, through the International Aluminium Institute, continues to support research to develop better methodologies and to test them using aluminium industry data (Gandhi & Diamond, forthcoming) and it is hoped that in future it will be possible to include such impact categories.

3.2.2. 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 life cycle inventory results which when summed 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 7.3.3. 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)*.

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

In addition to modelling the global aluminium industry's average potential environmental impacts, a select 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 2014 and 2015 were analysed, using the International Aluminium Institute's mass flow model (IAI 2015, Bertram et al, forthcoming). 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 <http://www.world-aluminium.org/statistics/massflow/>. This tool can be used to support life cycle assessments that require data on market supply by region.

In this analysis, five 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 (IAI 2014). 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. 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, 2013; European Aluminium Association, 2013), 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)
<i>LCI Dataset</i>	<i>Global (GLO)</i>	<i>Global (GLO)</i>	<i>Global (GLO)</i>
<i>Energy Dataset</i>	<i>Global (GLO)</i>	<i>China (CNA)</i>	<i>China (CNA)</i>
Scenario 2	Oceania (OCA) →	Oceania (OCA) →	China (CNA)
<i>LCI Data</i>	<i>Global (GLO)</i>	<i>Oceania (OCA)</i>	<i>Global (GLO)</i>
<i>Energy Data</i>	<i>Global (GLO)</i>	<i>Oceania (OCA)</i>	<i>China (CNA)</i>
Scenario 3	South America (SAM) →	Europe (EUR) →	Europe (EUR)
<i>LCI Data</i>	<i>Global (GLO)</i>	<i>Europe (EUR)</i>	<i>Europe (EUR)</i>
<i>Energy Data</i>	<i>Global (GLO)</i>	<i>Europe (EUR)</i>	<i>Europe (EUR)</i>
Scenario 4	Oceania (OCA) →	Oceania (OCA) →	Gulf Cooperation Council
<i>LCI Data</i>	<i>Global (GLO)</i>	<i>Oceania (OCA)</i>	<i>Gulf Cooperation Council (GCC)</i>
<i>Energy Data</i>	<i>Global (GLO)</i>	<i>Oceania (OCA)</i>	<i>Gulf Cooperation Council (GCC)</i>
Scenario 5	South America (SAM) →	North America (NAM) →	Canada (CAN)
<i>LCI Data</i>	<i>Global (GLO)</i>	<i>North America (NAM)</i>	<i>Canada (CAN)</i>
<i>Energy Data</i>	<i>Global (GLO)</i>	<i>North America (NAM)</i>	<i>Canada (CAN)</i>

Table 7: Example archetype scenarios considered for impact modelling

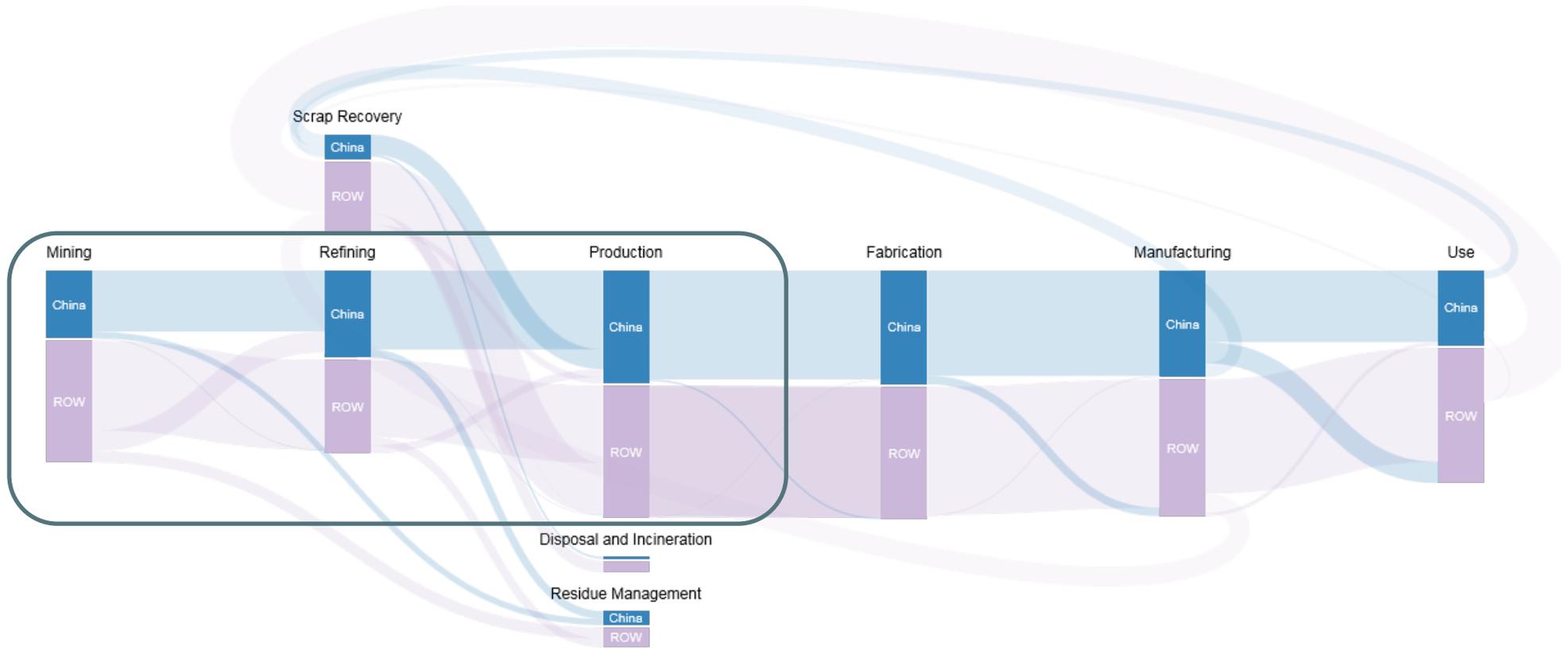


Figure 8: Mass flow example Scenario 1 – China

3.2.4. Impact Modelling

A primary aluminium cradle-to-gate model was previously developed as part of the impact modelling process for 2010 data (IAI, 2014); this model provides the foundation for the current impact assessment. The global model has been updated with the 2015 inventory datasets (foreground data) and background datasets available in GaBi 7 (2017). The scenario models are adapted from the global model by using the appropriate regional (or global) inventory and energy datasets of each unit process.

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 7 (using the global dataset). Electrolysis process impacts from Söderberg technology are only modelled at the global level. As discussed in Section 2.8, Söderberg smelter output only accounted for 5% of global production in 2015 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 7 and include:

- Limestone production (DE, 2016)
- Caustic soda production (DE, 2016)
- Petroleum coke production (EU28, 2013)
- Pitch production (DE, 2011)
- Electricity and fuel supply systems (2015)
- Transportation (GLO, 2015)

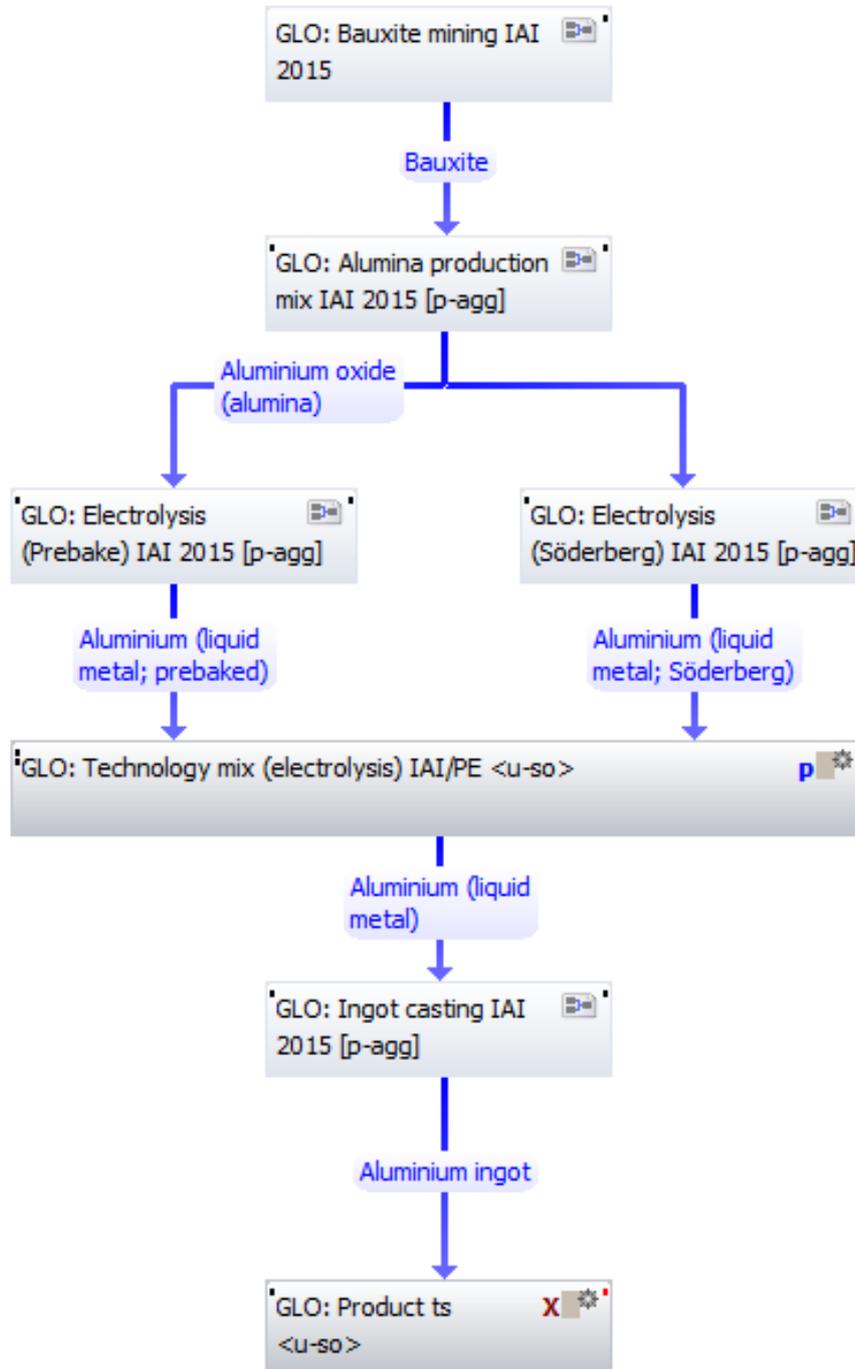


Figure 9: GaBi plan for global model

3.2.5. Electricity Generation

Primary aluminium production (in particular electrolysis and alumina refining processes) is an energy intensive process. Previous studies (IAI 2014) 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. The model is based on regionalised power consumption data as reported by industry respondents as part of the IAI 2015 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. The limitations and quality of background datasets is discussed in Section 3.3.4.



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

	Africa	Asia (ex. China)	China	Europe	GCC	North America	<i>Of which Canada</i>	Oceania	Russia & Other Europe	South America	World
Hydro	13,179	4,767	42,602	36,587	0	49,543	<i>(40,456)</i>	7,920	17,612	10,119	182,329
Coal	10,110	28,122	383,422	5,583	0	16,284	0	21,159	405	51	465,136
Oil	0	0	0	252	0	1	0	0	0	0	253
Natural Gas	0	0	0	2,635	63,269	582	0	0	0	5,553	72,039
Nuclear	0	0	0	8,828	0	648	0	0	0	0	9,476
Total	23,289	32,889	426,024	53,885	63,269	67,058	<i>(40,456)</i>	29,079	18,017	15,723	729,233

Table 8: 2015 Power Mix by Region (GWh)

The data in Table 8 differs from the power mix reported in <http://www.world-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/#data> 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.

3.2.6. 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.



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.

3.2.7. 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 materials:** All material and energy inputs and emission outputs associated with non-fuel input materials used in the production of primary aluminium (e.g. caustic soda, lime, aluminium fluoride, pitch & coke production)
- **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.
- **Transport:** Inputs and outputs associated with the seaborne, road and rail transport of input materials.

3.2.8. 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 the five archetype scenarios and consists of:

1. **Direct WSFP**, calculated using water consumption data, collected as part of the 2015 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.

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 (Buxmann 2016), summarised in Table 9 (Buxmann 2017). 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).

3.2.8.1. Direct WSFP

Water consumption of the site (input-output) is multiplied by a local characterisation factor known as its water scarcity index (WSI) (Pfister et al. 2009) to give a site specific WSFP. Water scarcity indexes are available through a KMZ file for use with Google Earth at: <http://www.esd.ifu.ethz.ch/downloads/ei99.html>. 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.

3.2.8.2. 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.

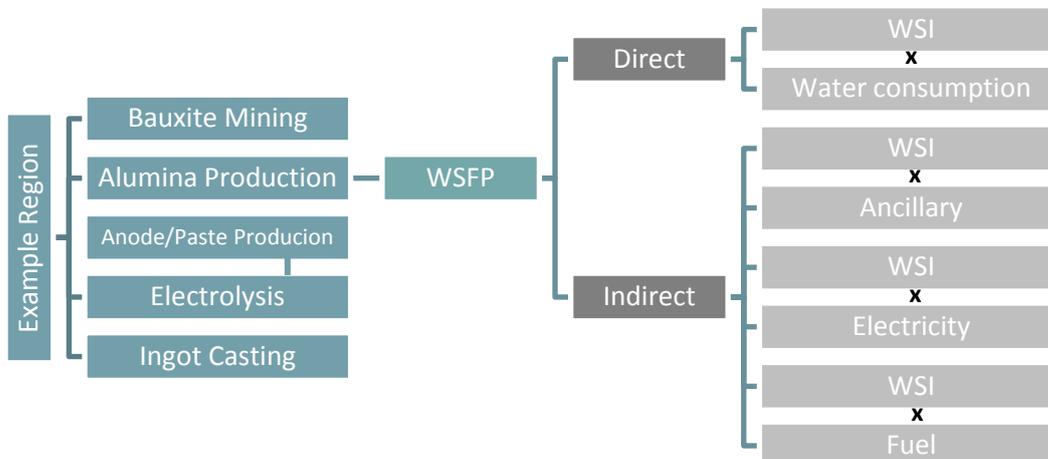


Figure 12: Example WSFP system for direct and indirect WSFP for alumina production

Region	Bauxite production	Bauxite total		Alumina production	Alumina (exc. Bauxite supply)		Primary aluminium production	Aluminium (direct)		Aluminium (indirect, exc. Alumina supply)		Mine to Ingot (direct + indirect)	
		WSFP	specific WSFP		WSFP	specific WSFP		WSFP	specific WSFP	WSFP	specific WSFP	WSFP	specific WSFP
	Mt	Mm ³ H ₂ Oe	m ³ H ₂ Oe/t	Mt	Mm ³ H ₂ Oe	m ³ H ₂ Oe/t	Mt	Mm ³ H ₂ Oe	m ³ H ₂ Oe/t	Mm ³ H ₂ Oe	m ³ H ₂ Oe/t	Mm ³ H ₂ Oe	m ³ H ₂ Oe/t
Africa	23	0.7	0.03	<1	0	0.9	2	0.06	0.03	16.7	9.8		
Asia (ex. China)	58	1.9	0.03	5	4.5	0.9	3	0.1	0.03	113.9	38.0		
China	65	2.1	0.03	59	51.7	0.9	32	1.07	0.03	722	22.9		
Europe (EU28 & EFTA)	2	0.1	0.03	6	5.2	0.9	4	0.36	0.09	17.9	4.5		
Gulf Cooperation Council	2	0.1	0.03	1	0.9	0.9	5	0	0	2.3	0.5		
North America	<1	0	0.03	7	5.2	0.8	4	0.3	0.07	11.5	2.6		
...of which Canada	-	0	0.03	-	-	0.9	3	0.03	0.01	6.7	2.3		
Oceania	81	0.9	0.01	20	17.5	0.9	2	0.03	0.02	4.6	2.3		
Russia and Other Europe	7	0.2	0.03	4	3.5	0.9	4	0.12	0.03	21	5.8		
South America	48	3.5	0.07	13	8.8	0.7	1	0.06	0.05	12.7	9.8		
Global	286	9.5	0.03	115	97.3	0.9	57	2	0.03	923	16.3	1032	18

Table 9: Regionalised Water Scarcity Footprint (WSFP) per unit process (differences due to rounding), Buxmann 2017

Scenario	Bauxite		Alumina				Aluminium					Mine to Ingot
	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	Specific Direct WSFP	Specific Indirect WSFP (ex. alumina)	Specific Total WSFP = H + J + K
	m ³ H ₂ Oe/t Bx	t Bauxite / t Alumina	m ³ H ₂ Oe/t Alumina		m ³ H ₂ Oe/t Alumina	t Alumina / t Aluminium	m ³ H ₂ Oe/t Al		m ³ H ₂ Oe/t Al	m ³ H ₂ Oe/t Al	m ³ H ₂ Oe/t Al	
GLO	<i>GLO</i>	0.03	5.5	0.2	<i>GLO</i>	0.7	1.9	1.9	<i>GLO</i>	0.03	16.3	18
1	<i>CNA</i>	0.03		0.2	<i>CNA</i>	0.8		2.0	<i>CNA</i>	0.03	22.9	25
2	<i>OCA</i>	0.01		0.1	<i>OCA</i>	0.8		1.8	<i>CNA</i>	0.03	22.9	25
3	<i>SAM</i>	0.07		0.4	<i>EUR</i>	1.1		2.8	<i>EUR</i>	0.09	4.5	7
4	<i>OCA</i>	0.01		0.1	<i>OCA</i>	0.8		1.9	<i>GCC</i>	0.00	0.5	2
5	<i>SAM</i>	0.07		0.4	<i>NAM</i>	0.7		1.9	<i>CAN</i>	0.01	2.3	5

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

* Direct and Indirect WSFP

3.3. Results and Discussion

3.3.1. Impact Category Indicator Results²

The impact category and additional indicator results (including GWP breakdown) have been calculated using GaBi version 7 software (2017). Water scarcity footprint results are calculated in accordance with ISO 14046 (Buxmann, 2016). All results are reported per tonne aluminium ingot.

	Global	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
<i>Bauxite → Alumina → Aluminium</i>	<i>GLO</i>	<i>CNA→CNA→CNA</i>	<i>OCA→OCA→CNA</i>	<i>SAM→EUR→EUR</i>	<i>OCA→OCA→GCC</i>	<i>SAM→NAM→CAN</i>
Acidification Potential (AP) [kg SO ₂ -Equiv.]	100	110	100	30	50	10
Depletion of fossil energy resources (DFE) [MJ]	166,000	186,000	180,000	94,000	183,000	50,000
Eutrophication Potential (EP) [kg Phosphate-Equiv.]	7	6	6	3	5	1
Global Warming Potential (GWP 100 years) [tonne CO ₂ -Equiv.]	18	20	19	7	15	5
Ozone Layer Depletion Potential (ODP) [kg R11-Equiv.]	1. 1E-8	3.1E-9	2.8E-9	1.5E-8	2.3 E-9	3.6E-9
Photochemical Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	7	8	7	2	4	2
Water Scarcity Footprint (WSFP) [m ³ Water-Equiv.]	18	25	25	8	2	5

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

² 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.

3.3.2. Contribution Analysis

At the global level an analysis of the relative contribution of the process categories outlined in Section 3.2.7. 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 all impact categories considered in this study.

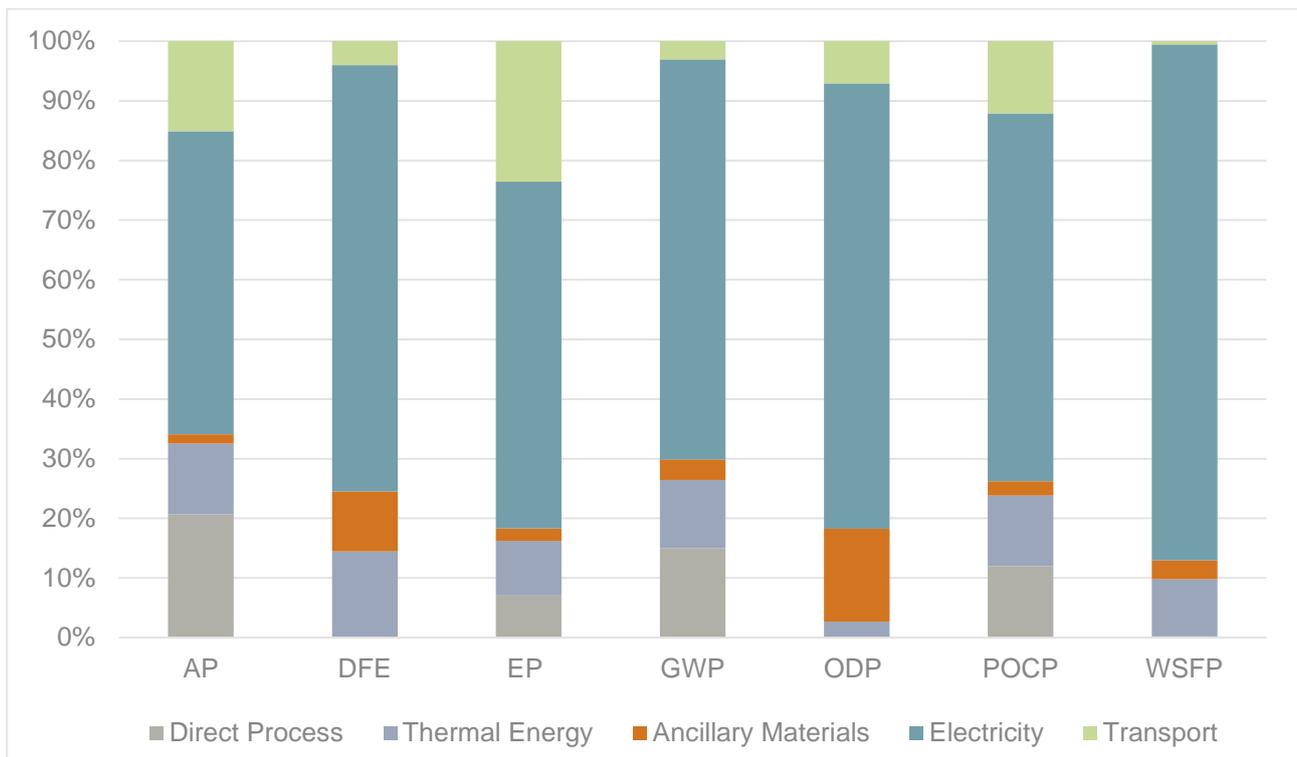


Figure 13: Contribution of key process types to global impact indicator category results

A similar analysis of process contribution across the five 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.

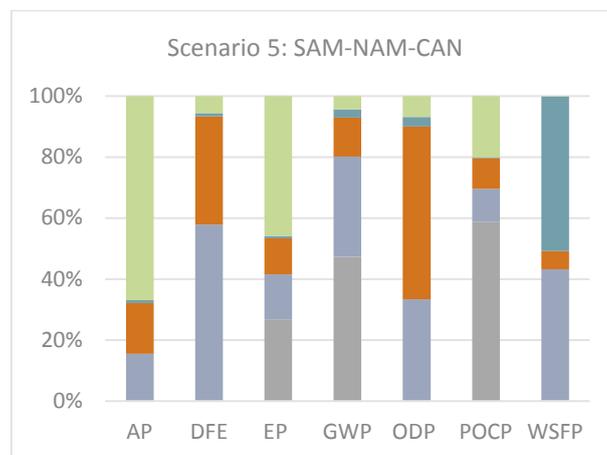
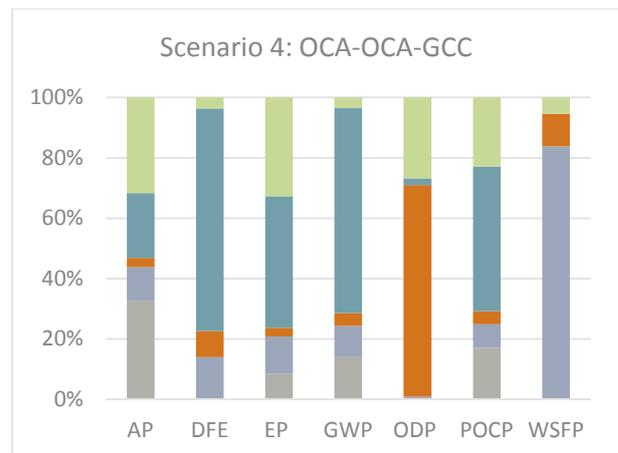
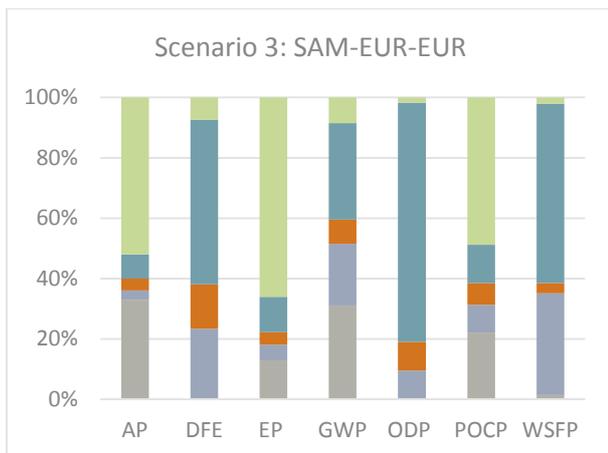
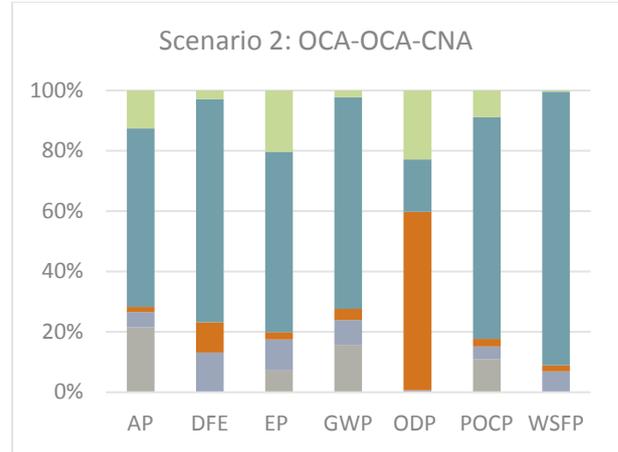
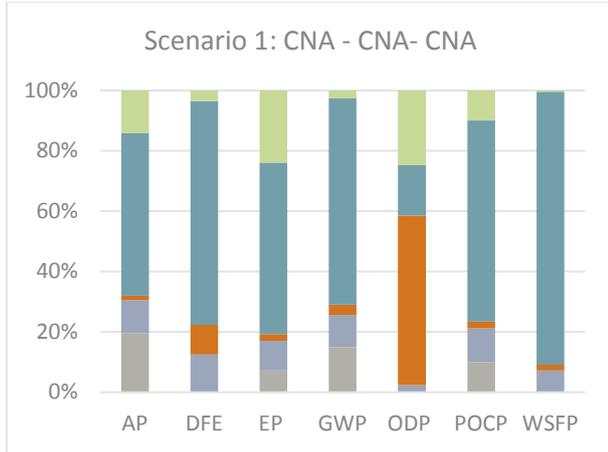


Figure 14: Relative contribution of each process type to impact category indicator results by scenario

3.3.3. Relative Contribution of Aluminium Production Unit Processes to GWP

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.

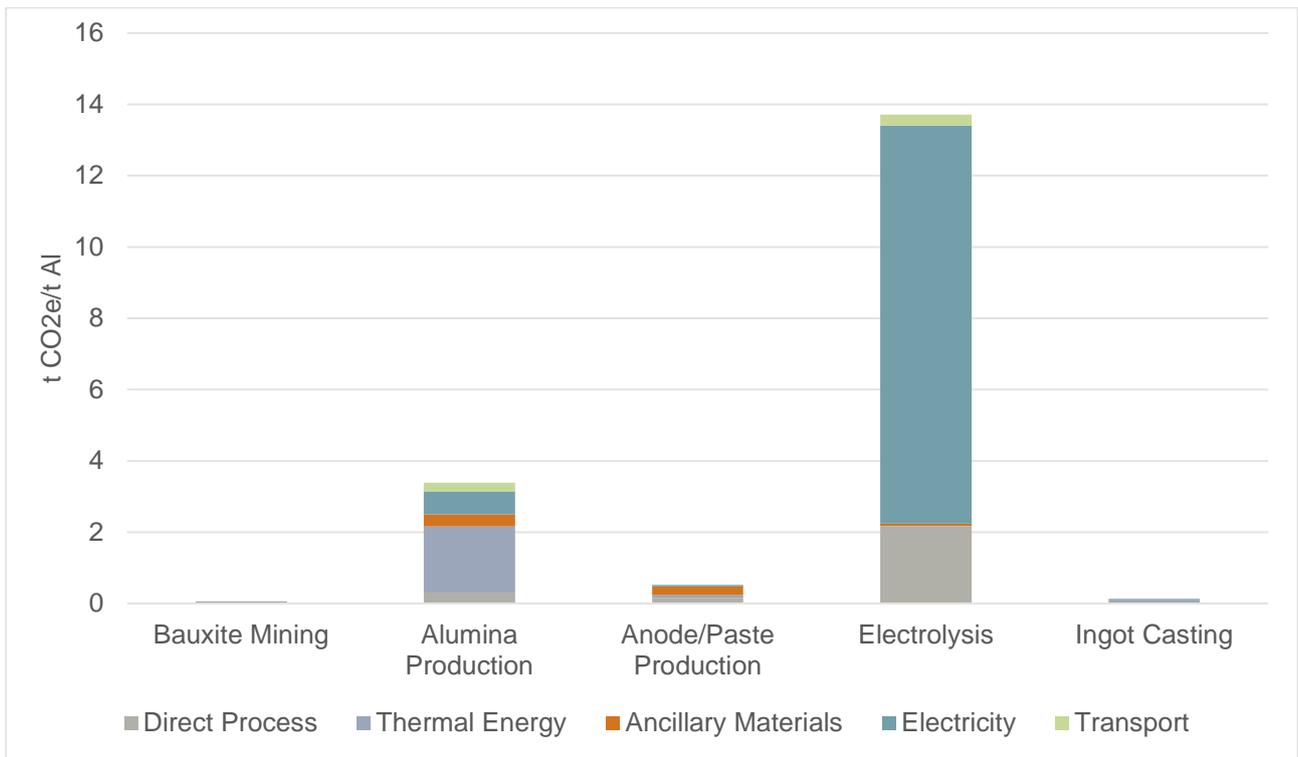


Figure 15: Global GWP by unit process and process type

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 GWP 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.

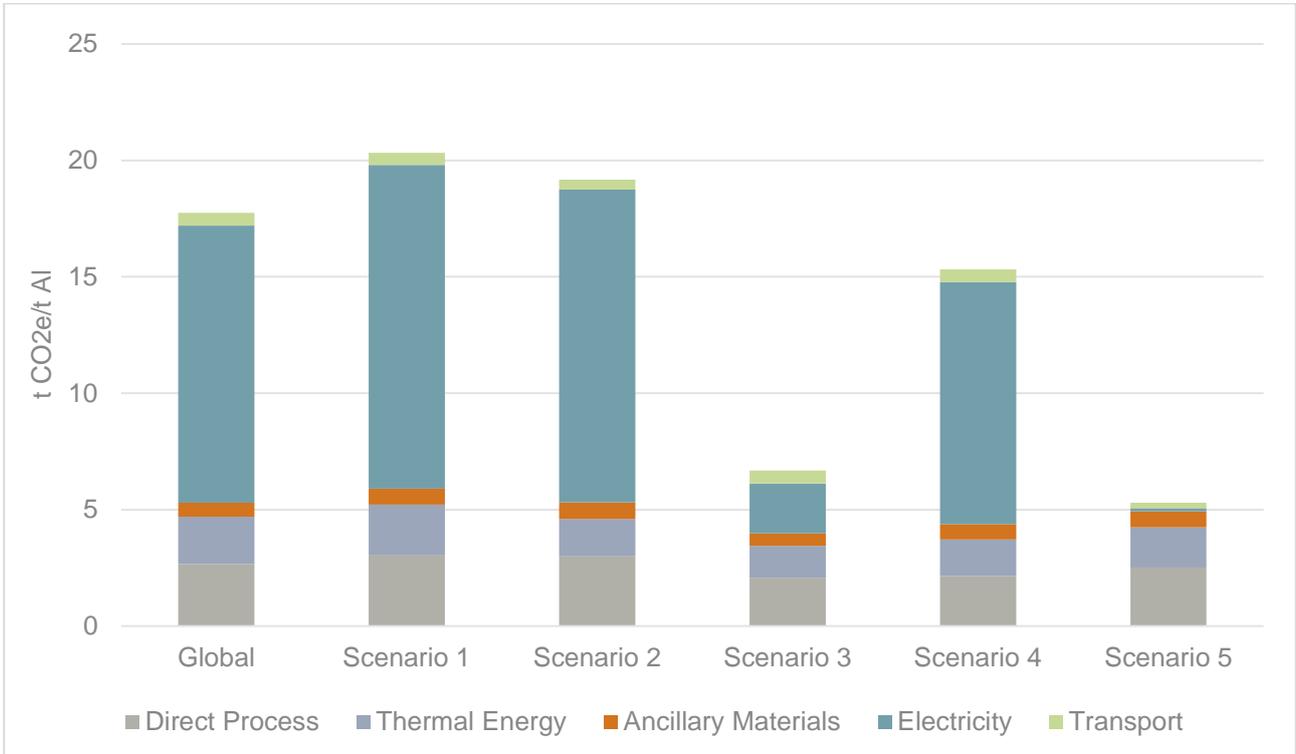


Figure 16: GWP by scenario and by process

3.3.4. Electricity: Background Data

Significant shifts in the location of primary aluminium production (in particular refining and smelting) over the past decade have led to significant changes in the global power mix. Increased aluminium production in China, which is predominately based on coal-fired electricity (China's grid is 70% coal, but the aluminium industry specific power mix in China is 90% coal, with the remainder mostly hydropower), has increased the contribution of background processes to impact category indicator results at the global level. Although an increase in the global impact indicator results for 2015 compared to 2010 was expected (on the back of China moving from a 38% to 55% share of global electrolytic production), the significant, and increasing influence that background datasets have on LCIA results necessitates further investigation of existing background data and assumptions available to practitioners in life cycle software and data providers.

The contribution analysis in Section 3.3.2 highlights the impact that electricity supply has on environmental impact; as such, further analysis of the representativeness of Chinese background datasets in LCA databases was conducted as part of a separate study (IKE, 2017). In 2016, IAI commissioned a project to understand better the quality of background data available in existing life cycle databases through the production of a provincial level, electricity supply model. Although, a number of smelters in China have captive power plants which may perform better than the average for the province, for the purpose of this modelling, provincial averages are considered a suitable, and likely conservative, proxy. The development of a provincial level model also ensures that the model is nuanced enough to reflect both the current geographical spread of aluminium smelters in China, but also future growth (and decline) in provinces as a share of total Chinese production in the future. The IKE model is populated with the latest data (year 2014) for coal and hydropower plants to provide a robust foundation for comparison with existing databases.

Two of the leading life cycle databases, ecoinvent and GaBi, provide background data with differing levels of detail and flexibility. ecoinvent provides Chinese electricity LCI data at sub-provincial level and is reflective of the current grid mix, rather than the industry mix of 90% coal and 10% hydropower (ecoinvent, 2017). GaBi on the other hand provides data at a national level and while industry power mixes can be modelled, it lacks the transparency and the flexibility needed to reflect the spread of aluminium production across provinces.

Aluminium production in China occurs in a cluster of provinces (Shandong, Xinjiang, Henan, Inner Mongolia, Gansu and Qinghai) and as such, the electricity supply from power plants in these regions should be reflected (coal quality, technology, efficiency etc.) and weighted accordingly in the impact modelling phase. It is also important to consider regions where it is known that thermal power is the source for 100% of primary aluminium production and grid mixes should be adapted accordingly to reflect industrial usage (Table 12).

The data generated from the IKE study were used by the IAI Secretariat to develop a Chinese aluminium industry power consumption (and associated impacts) model for comparison with the results included in this study. The analysis, summarised in Table 12, indicates that the IKE result for GWP impact of electricity used in electrolysis in China (13,562 kWh/t Al) is currently aligned with the GaBi model result (approx. 13kg CO_{2e}./kg Al) but significantly lower than the results generated using the equivalent production-weighted provincial level data in ecoinvent (approx. 18kg CO_{2e}./kg Al). The spread of possible results is highlighted in Figure 17.

Province	% Chinese aluminium production	% thermal power (grid)	% thermal power (Al ind'y)	GWP (kg CO ₂ e/kWh), using grid mix			GWP (kg CO ₂ e/kWh), using Al industry power mix		
				IKE	GaBi	ecoinvent	IKE	GaBi	ecoinvent
Shandong	26%	95%	100%	0.95	No provincial level data	1.39	0.98	No provincial level data	1.40
Xinjiang	19%	84%	100%	0.97		1.23	1.07		1.46
Henan	10%	96%	100%	1.07		1.41	1.05		1.46
In'r Mongolia	8%	88%	100%	1.20		1.82	1.35		1.99
Gansu	7%	59%	100%	0.65		0.84	1.04		1.40
Qinghai	7%	22%	22%	0.28		0.31	0.28		0.31
Yunnan	4%	15%	15%	0.24		0.53	0.24		0.53
Ningxia	4%	90%	100%	1.02		1.50	1.09		1.55
Guizhou	3%	60%	60%	0.64		0.91	0.64		0.91
Shanxi	2%	96%	100%	1.09		1.50	1.07		1.53
Shaanxi	2%	92%	100%	0.84		1.26	0.91		1.34
Chongqing	2%	48%	48%	0.62		0.96	0.62		0.96
Guangxi	2%	49%	49%	0.50		0.77	0.50		0.77
Liaoning	1%	68%	68%	1.20		1.47	1.20		1.47
Sichuan	1%	19%	19%	0.26		0.40	0.26		0.40
Hunan	1%	59%	59%	0.62		0.89	0.62		0.89
Fujian	0%	68%	68%	0.74		0.88	0.74		0.88
Hubei	0%	40%	40%	0.44		0.52	0.44		0.52
Hebei	0%	91%	100%	1.13		1.42	1.11		1.48
China	100%	77%	90%	0.92	N/A	1.15	0.93	0.97	1.31
GWP for electricity used in electrolysis (kg CO₂e/ kg Al)				11.7	N/A	16.3	12.6	13.2	18.2

Table 12: Chinese aluminium industry GWP by province for electricity used in electrolysis (IKE, 2017, GaBi 2017, ecoinvent 2017)

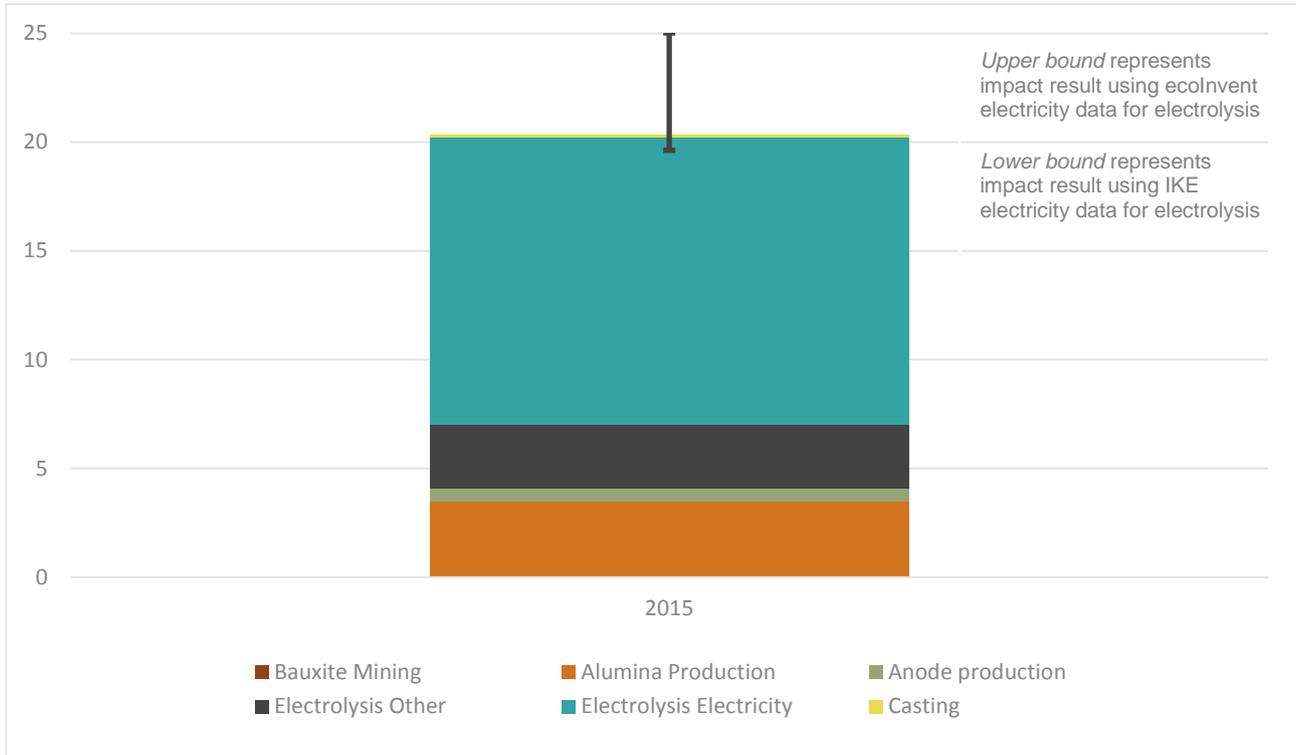


Figure 17: Scenario 1 (China) GWP result by unit process for 2015

The issue of background data is not limited to Chinese electricity. A similar issue with background data quality has an impact on the results for Scenario 4 (OCA-OCA-GCC). The absence of a direct regional (GCC/Middle East) or country level (Bahrain/Oman/Qatar/Saudi Arabia/United Arab Emirates) dataset for electricity generation from natural gas in GaBi 7 leaves LCA practitioners with a challenging choice on a suitable proxy dataset to use for modelling.

In Scenario 4, a proxy dataset is used based on *electricity from natural gas in Malaysia* but this dataset (and all other *electricity from natural gas* datasets that are available in the software) are national averages that are relatively outdated (year 2013) and do not reflect the best available technology that is in place, and supplying smelters, in the Gulf region. Estimates from gas turbine producers (GE Power 2016) supplying the region suggest emission factors are significantly lower (approximately 0.3-0.4kg CO₂e/kWh) when compared to existing assumptions in third party databases (approximately 0.4-0.7kg CO₂e/kWh). Such limitations mean that it is likely that the potential environmental impacts, particularly for regions with new capacity, where best available technology is utilised, are likely to be lower than the modelled results.

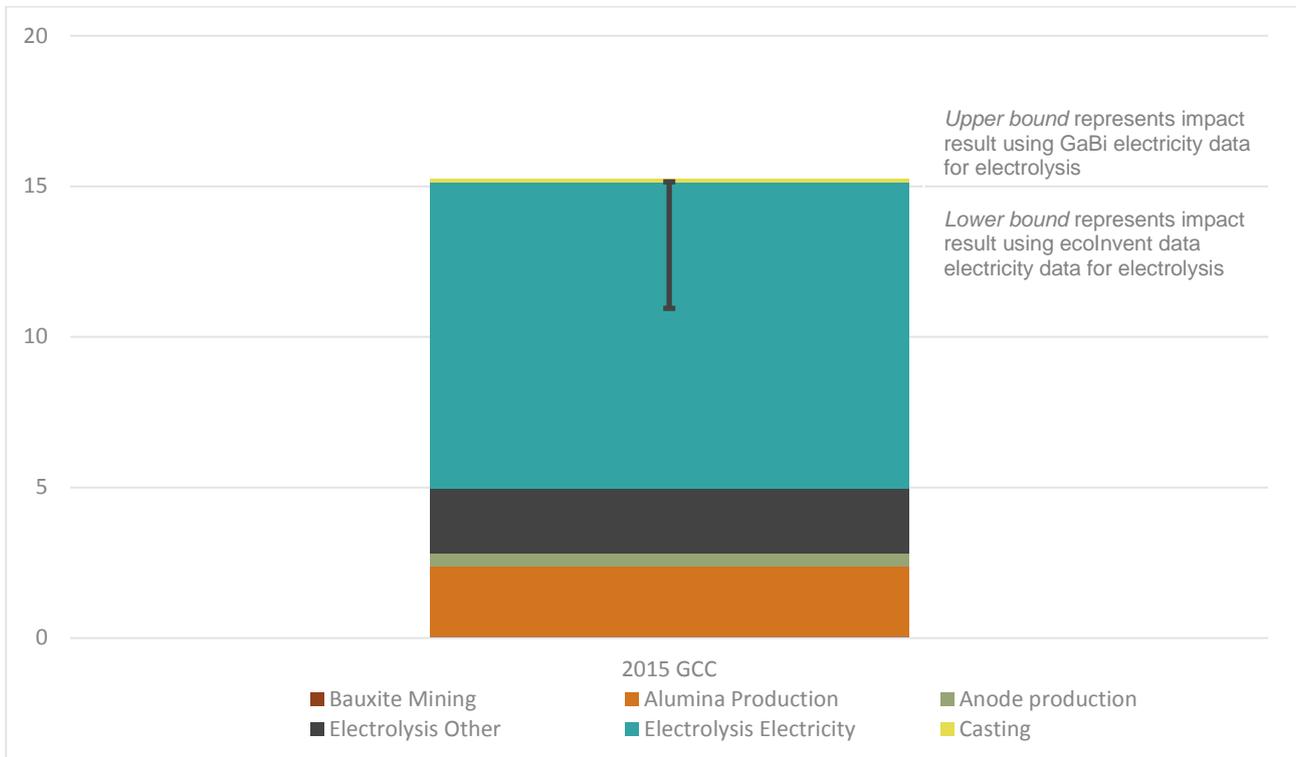


Figure 18: Scenario 4 (OCA-OCA-GCC) GWP result by unit process for 2015

The Institute is seeking the inclusion of up to date and regionalised or provincialised background data, that is reflective of industry, in life cycle databases. The 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. LCA practitioners should try to use as specific data as possible but recognise the inherent challenges associated with representativeness (temporal, spatial and technological) of background data in third party databases and the impact it can have on results.

3.4. Interpretation and Conclusions

3.4.1. Significant Issues

The results presented in this study show that the impacts associated with the production of electricity are the most significant contributor to overall environmental impact of primary aluminium production at a global level; between 50% and 90% across all 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 across all impact indicator results compared to primary aluminium production based on hydropower or gas.

Electricity and direct process emissions are the most significant contributors to GWP at the global level, contributing around 65% and 15% respectively. This is in line with the findings of previous analyses (IAI 2014). Electricity and direct process emissions are also the most significant contributors in four of the five example scenarios. Scenario 5, where hydropower electricity dominates, is the exception to this; the main contributors are process emissions (around 45%) and thermal energy (around 35%).

Although the share of thermal power consumed by the aluminium has increased over the past decade³, as production has grown in China and the GCC, the use of best available smelting technologies in these locations, paired with the closure of older, less efficient facilities has reduced process energy intensity⁴.

3.4.2. Limitations

Data quality: as reported in Chapter 2, all reported data points were checked individually using a systematic approach. Significant variations (± 2 STD) in reported data, or $\pm 15\%$ when compared with 2010 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 representativeness of the inventory data. Overall, reporting rates could be improved with greater coverage of newer and emergent regions of production such as China and Other Asia. It is intended that the Life Cycle Survey form be reviewed prior to the next round of data collection (2021) in order to simplify the reporting process and encourage new industry participants to report key environmental data.

³ <http://www.world-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/#histogram>

⁴ <http://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/#linegraph>

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. As such, a detailed study (IKE, 2017) provides up to date data on Chinese power generation at a provincial level for comparison with background data and assumptions that exist within life cycle databases and the influence that such differences have on results.

3.4.3. *Conclusions and Next Steps*

Overall, the results from this study validate previous findings (IAI, 2014) and highlight the significance of electricity production on potential environmental impacts of primary aluminium production at the global level. The use of industry specific power mixes is vital in life cycle modelling as often regional power mixes are not representative of the industry. Dependence on background datasets for processes with significant contribution to the industry's potential environmental impact comes with inherent limitations and provides an opportunity for further work in the future. The importance of electricity production is reduced when evaluating the potential environmental impacts related to aluminium production from hydropower dominated regions.

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 2022 representing data for the year 2020.

This study provides an example of the Institute's first steps towards integrating life cycle assessment with mass flow analysis. In future work, it is hoped that this can continue to be developed and used by practitioners as a tool in decision making, allowing for impact modelling both across space and through time.

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 increased reporting coverage from 2010 levels for key data points including energy input (inclusion of Chinese estimates) and the inclusion of new inventory data on land use for bauxite mining and residue storage. These new additions address two areas that were identified in the 2010 third party life cycle review as areas for improvement.

Following on from this study, the fourth such iteration of the Institute's Life Cycle Inventory, a full review of the industry survey along with relevant impact categories will take place. The review panel has suggested inclusion of additional indicators such as potential species loss caused by land occupation and transformation and potential respiratory effects (PM10 equivalents) be considered for future studies.

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. The evaluation of background data related to electricity generation in China, is an example of such a case. 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 and the Institute will seek integration of revised Chinese provincial energy models and data into existing third-party databases. 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.

4. Final Remarks and Recommendations

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 2015 dataset for the first time includes regionalised, 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 (and provincialised) 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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