GLOBAL LIFE CYCLE INVENTORY DATA FOR THE PRIMARY ALUMINIUM INDUSTRY

2010 DATA

FINAL

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Executive Summary

The collection of global aluminium industry data for use in life cycle assessments was initiated by the *International Aluminium Institute* (IAI) Board in 1998 with the following resolution:

> "The Board of Directors of the *International Aluminium Institute* desires that the Institute develop as complete an understanding as possible of the positive contributions that the aluminium makes to the environmental and economic well-being of the world's population; of any negative economic or environmental impacts that its production may cause; and of the balance between these positives and negatives during the entire "life cycle" of the material."

This *Global Life Cycle Inventory Data for the Primary Aluminium Industry* report is an update for data year 2010, following similar reports for 2000 and 2005. It has been prepared with an objective to collect all significant life cycle inventory (LCI) data (raw materials and energy use, emissions to air and water, solid waste generated) on primary aluminium ingot production from bauxite ore, at the global level.

This report demonstrates the global aluminium industry's dedication to report openly its environmental impacts and to publish regularly the latest and most representative LCI data possible. As such, this 2010 report is the reference material for aluminium environmental assessments and its use is to be considered as mandatory for life cycle practitioners. Some data are collected more regularly and this report will be updated on an annual basis with such data as they become available.

From 2005 to 2010 world primary aluminium production increased by almost 30%, and environmental performance improvements took place through strong investments in new large-scale production capacities and phasing out of old plants. Achievements included reduction of perfluorocarbon (PFC) air emissions (by 40% per tonne Al), polycyclic aromatic hydrocarbon (PAH) air emissions (by 50% per tonne Al) and of spent pot lining (SPL) solid waste landfilled (by 45% per tonne Al).

1. Goal and scope

The purpose of this inventory report is to characterize accurately and at the global level resource inputs and significant environmental releases associated with the production of primary aluminium.

The collected data serves as a credible basis for subsequent life cycle assessments (LCA) of aluminium products.

1.1 Process description and system boundaries

Primary aluminium production includes the following unit processes:

- bauxite mining;
- alumina production (from bauxite);
- anode production (including production of *Prebake* anodes and *Søderberg* paste);
- electrolysis (including *Prebake* and *Søderberg* technologies);
- ingot casting.

Unit process descriptions are reported in Appendix A.

The inter-relationship of these unit processes is shown in the flow diagram in Appendix A, which provides an overview of material input flows. The primary aluminium production process can be summarized as follows: aluminium is extracted from bauxite as aluminium oxide (alumina); this oxide is then broken down through an electrolysis process into oxygen, emitted as CO_2 by reaction with a carbon anode, and aluminium as liquid metal; this molten aluminium is cast into ingots, the usual form suitable for further fabrication of semi-finished aluminium products.

Relevant background processes not documented in the present work are specified in the flow diagram in Appendix A, outside of the dotted line which indicates the scope of this study.

Such additional unit processes (in particular energy carrier production and production of raw materials such as petrol coke, pitch and caustic soda) have not been added to the in-scope processes in order to avoid non-elementary flows. Life cycle practitioners who will use the data of this report may include such additional unit processes from alternative databases[1].

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[1] Care should be exercised when using data in this report on air emissions from fuel combustion, namely particulates, SO_2 and NO_x emissions. Facilities surveyed for this report delivered data on fuel combustion emissions for improved reliability, in particular to reflect the impact on SO_2 emissions of actual sulfur content in combusted fuel oil. Accordingly life cycle practitioners are recommended to remove their data on particulates, SO_2 and NO_x emissions, in order to avoid double counting. This applies only to fuel combustion and not to "pre-combustion" data.

Special care is needed to include the appropriate electricity supply, according to reference information collected by IAI on power sources (http://www.world-aluminium.org/statistics/primary-aluminium-smelting-power-consumption).

Example year 2012 data from IAI is shown in Table 1, with a historical perspective (1980-2012) on global power mix illustrated in Figure 1.

	Africa	North America	South America	Asia (ex China)	Europe	Oceania	GCC	China	World
Hydro	48%	77%	85%	9%	81%	24%	0%	10%	38%
Coal	52%	22%	0%	91%	7%	75%	0%	90%	53%
Oil	0%	0%	0%	0%	0%	0%	0%	0%	0%
Natural Gas	0%	1%	15%	0%	3%	0%	100%	0%	8%
Nuclear	0%	1%	0%	0%	8%	0%	0%	0%	2%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table 1: Year 2012 aluminium industry power mix data

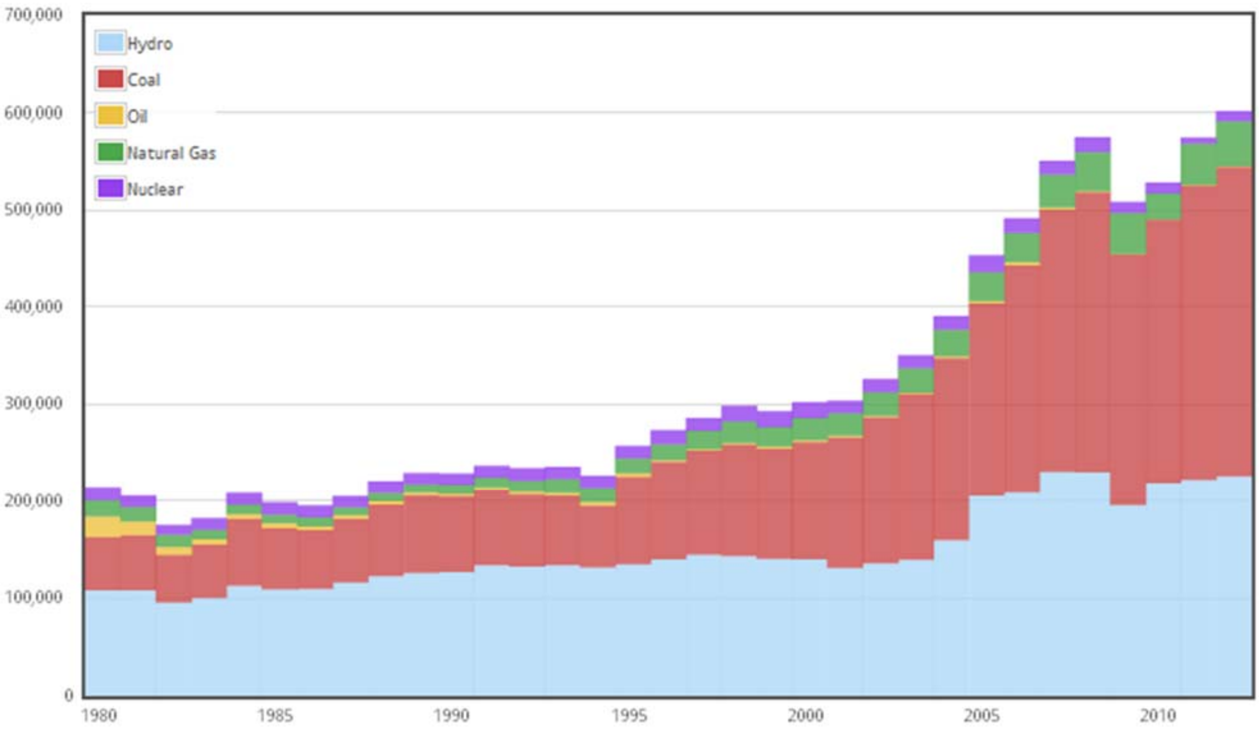

Figure 1: Global aluminium industry power mix, 1980 – 2012 (www.world-aluminium.org/statistics)

Only energy consumption figures (kg coal, diesel oil, heavy oil; m^3 natural gas; kWh electricity) and direct (Scope 1) carbon dioxide emissions are documented in this inventory; indirect Scope 2 and Scope 3 (US EPA & IAI, 2008) carbon dioxide emissions data are not included, but can be calculated using appropriate background data from alternative databases

Data related to the transport of materials are covered for the first time in this report. They are recorded as bauxite and alumina transport distances per 1,000 kg of product (tkm).

1.2 Data selection

This report contains only as-collected data for the calendar year 2010. Selection of data categories for this inventory was 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 A.

1.3 Reference flow and allocation

For each unit process the reference flow is 1,000 kg of product. For the whole primary aluminium process as shown above, 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 remelt or recycled aluminium, which is considered outside the scope of the present work.

Thus, the overall average from the survey results for the ingot casting process yields a higher mass output (1,062 kg) than the corresponding electrolysis metal input (971 kg), due to a “cold metal” contribution from remelt (50 kg remelt ingot) and recycled (23 kg external scrap) aluminium. This cold metal contribution is excluded by adjusting all inputs and outputs from the survey average by a factor of 0.94, calculated as follows:

(electrolysis metal + alloy additives = 990 kg)/(total metal input – scrap output sold = 1,062 kg – 5 kg) = 0.94

According to the ISO standards (14040 and 14044) on LCA, this can be described as a situation of joint processes where a mass allocation approach is applied.

Further allocation is not relevant as there are no co-products resulting from the unit processes described in this study.

1.4 Primary aluminium production mass balance

This section describes the main component distribution of the mass flow to 1,000 kg primary aluminium output from 5,571 kg of bauxite input.

5,571 kg of bauxite is the average input mass for production of alumina (aluminium oxide). However there is always a significant water component in the bauxite, typically around 20 % (c. 1,000 kg). The non aluminium-containing part of the bauxite is disposed of as bauxite residue (2,614 kg) or recycled (5 kg). The mass of material output from the alumina production process is thus around 2,000 kg, after deduction of water and bauxite residue.

Aluminium oxide (alumina) is chemically reduced in the electrolysis process as follows, with a stoichiometric minimum requirement of 1,889 kg Al_2O_3 per 1,000 kg of primary aluminium.

$$2\ Al_2O_3 + 3C = 4\ Al + 3CO_2$$

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 CO_2 with oxygen from the atmosphere). Thus average net anode consumption (439 kg) is higher than the theoretical mass predicted by stoichiometric analysis (333 kg).

1.5 Geographic system boundary

The scope of this report is global and as such wherever reporting production percentages are shown these refer to global production numbers. Unfortunately data of sufficient quality was not available from the Chinese aluminium industry, which represents around 40% of global production. The geographical survey coverage is discussed further in section 2.

2. Data collection

Data was collected through a number of surveys of IAI member and reporting companies, which together covered the entire scope of the inventory:

- the 2010 Life Cycle Survey, where survey forms were designed in order to collect all required LCI data except those already collected through established annual IAI surveys:
    - http://world-aluminium.org/media/filer_public/2013/01/15/2010_lci_survey_questionnaire.xls
- the 2010 Energy Surveys:
    - http://world-aluminium.org/media/filer_public/2013/01/15/iai_form_es011.pdf
    - http://world-aluminium.org/media/filer_public/2013/01/15/iai_form_es001.pdf
    - http://world-aluminium.org/media/filer_public/2013/01/15/iai_form_es001a.pdf
    - http://world-aluminium.org/media/filer_public/2013/01/15/iai_form_es001d.pdf
- the 2010 Anode Effect (PFC) Survey:
    - http://world-aluminium.org/media/filer_public/2013/01/15/pfc001.pdf

Survey forms were sent out to statistical correspondents of all IAI members and reporting companies in early 2011 requesting data for the 2010 period. The values reported were assessed alongside previously reported values (standardised to per tonne of relevant product) to identify anomalous figures, either as a function of deviation from the 2010 data distribution or substantial change within facilities over time from 2000 or 2005. Plants were queried on these figures, which were then confirmed or amended. This data collection and processing was monitored by a dedicated life cycle data review group, itself reporting to the *IAI Environment & Energy Committee*.

All averages, unless otherwise identified are production weighted mean values per tonne of relevant production output (i.e. excluding production of those plants that do not report for a particular question). In some circumstances this methodology does not accurately reflect specific process features and so alternative approaches have been applied – these are clearly identified as such and are fully explained in Section 3.

Data reporting, trends and issues are further discussed in Section 4. Detailed results of the inventory analysis by process are reported in Appendix A.

2.1 Survey coverage

Figure 2 illustrates the global reported data coverage of the relevant IAI surveys for data year 2010 for each of the broad production process steps. Response rates using global production figures as the denominator are available for each individual data point in Appendix A.

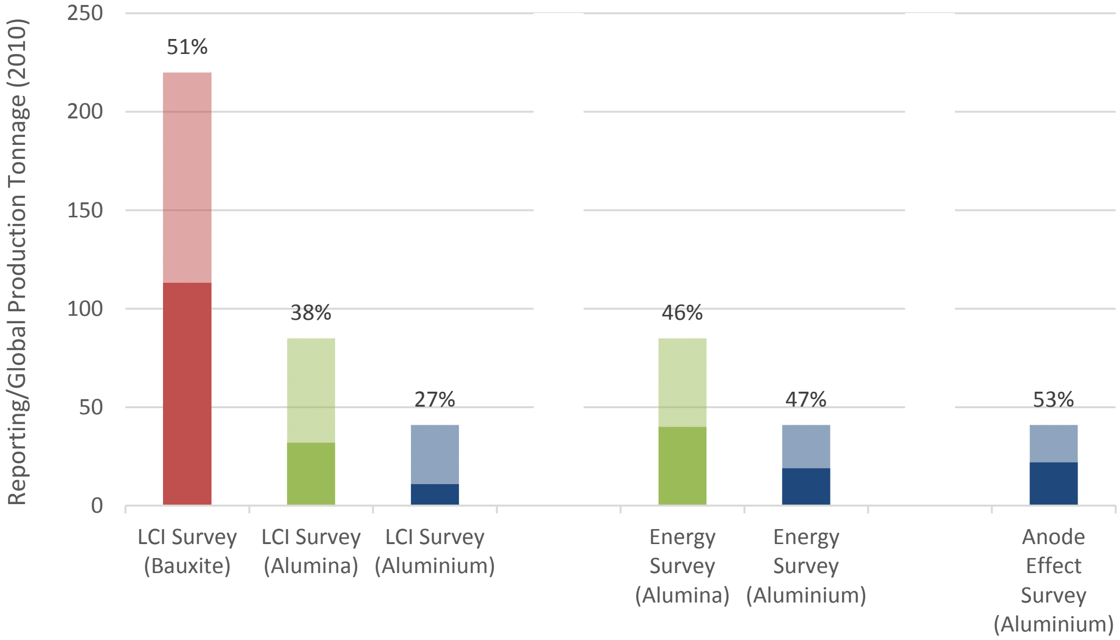

Figure 2: Response rates and global production figures for data year 2010

The Chinese aluminium industry (accounting for around 40% of the world's 2010 alumina and primary aluminium production) currently reports energy data to the IAI on an aggregated China-wide basis (via the China Nonferrous Metals Industry Association), and this forms the basis of the energy data published annually by the IAI online (http://www.world-aluminium.org/statistics) and included in Table 1 and Figure 1.

In addition, data on PFC emissions directly measured at a sample of Chinese smelters between 2006 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/).

However, such aggregated or sample data are not of a sufficient quality to include in a life cycle inventory. Therefore, the data included in this report includes no data from the Chinese aluminium industry. Throughout this report, wherever reporting production percentages are shown these refer to global production numbers that include China. Figure 3 illustrates the reported data coverage of the relevant IAI surveys for data year 2010 for each of the broad production process steps were Chinese production to be excluded from the denominator (ROW).

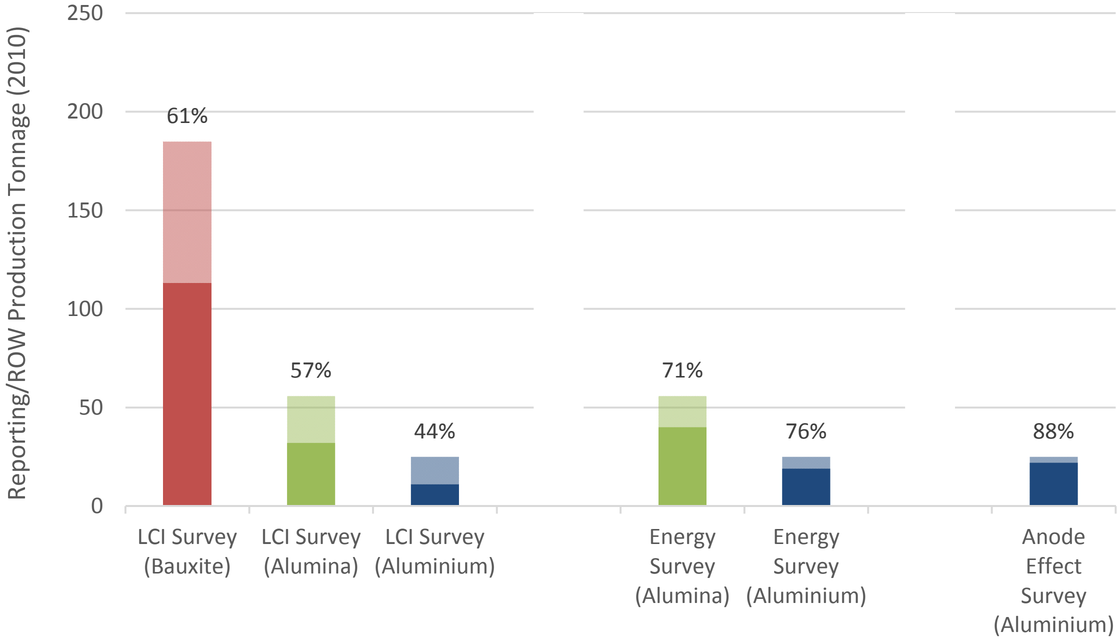

Figure 3: Response rates and production figures for data year 2010 excluding China

2.2 Technology coverage

Alumina production process data were supplied by facilities in operation in 2010 which were refining metallurgical grade alumina from bauxite ores only (according to IAI and European Aluminium Association (2013) <5% of global alumina production comes from non-bauxite sources). Chemical grade alumina, alumina from nephaline plants and alumina from other sources are out of the scope of this report.

The aluminium electrolysis unit process data was submitted by facilities operating all existing major technology types. Around 7% of the total production surveyed came from *Søderberg* technology, with the remaining 93% from *Prebake* facilities in the LCI survey. For information, China (which is not represented in the reported data) uses 100% *Prebake* technology.

2.3 Assumptions for non-reporting production

In the unit process data, no assumptions are made regarding data from non-reporting facilities. All input/output flows are derived only from reported data. As such, and with reference to Section 2.1 above, Chinese industrial data is not represented in the database, other than production data included in denominators for calculation of reporting percentages.

Data in the combined Summary inventory in Appendix A (per tonne of primary aluminium ingot), however is calculated based on a year 2010 global production weighted technology split between *Prebake* (89%) and *Søderberg* (11%) cell technologies (note difference to the 93:7 split above); this therefore assumes a non-reporting industry (including China) per technology performance equivalent to the reporting industry.

3. Data analysis

3.1 Data quality

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

- Precision (weighted mean values): all values presented in the text of this report represent production weighted mean values for worldwide aluminium processes;
- Standard deviation;
- Minimum and maximum values.

3.2 Averaging

A normal distribution of data is assumed. The following is a description of the methodologies used for averaging of inventory data and rationale for choice of methodology for specific datasets:

Weighted Mean

A production weighted average that 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 was reported (including zero values) for inclusion in the numerator. Non-reported or "blank" data is included in neither the numerator nor the relevant production in 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 2: 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

Industry Weighted Mean

The previous two methods are used to calculate averages for the majority of normalised data in the LCI, expressing a production weighted mean for reported data (including zero values), but excluding non-reporting production tonnage in denominators. However, for some data, specifically where there is an array of input/outputs per relevant process data (e.g. fuel mix), there is a need to “count” non reported datapoints, which are in effect equivalent to “zero values” and to include the reporting production in the denominator.

Such arrayed data is relevant where individual facilities are not representative of the industry as a whole and so an industry wide approach is required with the full array of available inputs/outputs. For example, seawater input should count non-reporting from plants that are not located by the sea (equivalent to zero values, but non-reported), as just counting coastal facilities is not a reflection of the industry as a whole. In the same way, non-reported (equivalent to zero values) transport distances for some transport modes should be counted, given that not all facilities have equal access to rail, road or sea transport. Fuel and power mix is the third example (demonstrated below), where the average split of the industry as a whole is the relevant average.

Thus industry weighted mean is a weighted average of a comprehensive array across the industry, not just the average of a single criterion per production mass.

	A	B	C	D	E	F	G	H
1	**Plant**	**Production tonnage (t)**	**Fuel 1 (kg)**	**Fuel 1 (kg/t)**	**Fuel 2 (kg)**	**Fuel 2 (kg/t)**	**Fuel 3 (kg)**	**Fuel 3 (kg/t)**
2	**U**	10	100	10	30	3		
3	**V**	20						
4	**W**	10			20	2		
5	**X**	25	50	2	50	2	50	2
6	**Y**	100						
7	**Z**	300	60	0.2	300	1		
8	**TOTAL**	465	210	12.2	400	8	50	2

Table 3: Example data for explanation of Industry Weighted Mean

Weighted Mean (Fuel 1) = 210/335 = **0.63 kg/t**

BUT

Industry Weighted Mean (Fuel 1)
=SUM(C2:C7)/(SUM(B2:B7)-
SUMPRODUCT(ISBLANK(C2:C7)*ISBLANK(E2:E7)*ISBLANK(G2:G7)*B2:B7))
= 210/(465 – (100+20)) = 210/345 = **0.61 kg/t**

Aluminium Industry Weighted Mean
As in the example above, aluminium industry weighted mean is the industry weighted mean expressed per tonne aluminium.

Industry Weighted Means have been used for the following situations:

- Sea water use by a limited number of respondents for wet scrubbing[2]. Non-reporting (equivalent to zero values) from plants that are not located by the sea are included;
- Transport: non-reported (equivalent to zero values) should be counted, given that not all facilities have equal access to rail, road or sea transport;
- Fuel and power mix: where the average split of the industry as a whole is the relevant average.

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[2] Sea water use for wet scrubbing (smelter exhaust fume cleaning systems) is relevant to a limited number of companies. However, as the process dilutes smelter air emissions into sea water to harmless concentrations; it includes significant quantities of input and discharged sea water.

4. Data trends and statistical differences from 2005 to 2010

Changes (and lack of change) in inventory data between the 2005 and 2010 datasets can reflect:

- Differences in the composition of reporting groups, quality of survey questionnaire(s) or reported data;
- Real changes in global and/or reporting industry performance over the same period.

In this section, some differences between the 2005 and 2010 inventories are explored, with respect to these functions.

4.1 Changes in composition of industry reporting and/or data quality

A change in reporting group and low completeness (low response rates) in either the 2005 or 2010 survey, mean that apparent trends over this period can sometimes be considered unreliable. Comments in this section explore data-driven differences (as opposed to performance-driven differences) organised by process and compare 2010 data to 2005 data (IAI, 2007).

For all processes, freshwater consumption/use data received particular attention during the 2010 survey development, reporting quality control and analysis stages, due to uncertainties identified in previous surveys. As a result, the freshwater data presented in the 2010 inventory can be considered to have a substantially higher reliability than previous inventories.

4.1.1 Bauxite Mining

Sea water input and ***output*** (without consumption. i.e. output equals input) is an order of magnitude higher in 2010 compared to 2005, but this should not be interpreted as a significant trend as only one facility reported in 2010, which is different to the single respondent in 2005 (who did not complete a survey, rather than did not report sea water use). Only mines located at the coast use sea water for washing bauxite and the quantity used varies considerably at each location.

Fuels and electricity consumption appear quite different from 2005, a function of a different reporting group. Such consumption is very small compared to subsequent thermal and electrochemical processes.

Particulates air emissions appear to be down by 80%. The 2005 data was high due to an erroneous response from a mine (reporting a figure an order of magnitude higher than other respondents), which did not participate in the 2010 survey. The 2010 data can be considered more reliable.

4.1.2 Alumina Production

Fresh water input is 70% lower than 2005. The 2005 data was exceedingly high due to erroneous responses from three refineries, which did not participate in the 2010 survey. The 2010 data can be considered more reliable.

Sea water input and ***output*** (without consumption. i.e. output equals input) appears to have increased five-fold. A significantly higher response rate in 2010 compared to 2005 means that this value can be considered more reliable than previous data.

Other by-products recycled is reported as 2005 data as the 2010 survey for this data point contained an error, leading to incorrect values being reported.

4.1.3 Anode Production, Electrolysis & Ingot Casting

Fresh water use
Uncertainties were identified in 2005 with reported values for ***fresh water input*** and ***output***, reflecting differences in facilities' measurement of freshwater use and consumption that varied between reporters, reflecting water availability at given locations (with those facilities that are water constrained having more developed systems for measurement) and also variability in understanding among reporters on definitions of water use, consumption etc.

Accordingly this subject was given special attention for the 2010 survey and a consistent description of water use was codified in the survey. Reporters were asked to report freshwater input and output for each of the unit processes anode production, electrolysis and ingot casting. Many companies only record water use for the location as a whole and so responded with figures for their entire plant, (i.e. for the 3 processes together). Accordingly, indicative split water figures specific to unit processes and developed from those reporters that submitted separate process data, are for information only.

Water is commonly used throughout the aluminium industry for cooling purposes. Such usage can be singular (input-cooling-output), which tends to output a similar volume to input or multiple (through water recycling systems), which again results in an output similar to input, but also reduces the net water input. Cooling water is discharged after use, with constant monitoring of the quality of water effluents.

- *Cooling uses* account for 88% of discharged water quantities (6.5 m^3 H_2O/t Al)[3].
- *Other uses* account for 12% of discharged water quantities (1 m^3 H_2O/t Al). Likely uses include wet scrubbing and other limited, site specific processes.
- *Water consumption*, that is water that is input to the system but not output, is derived from data reported from a limited number of plants that use water for direct cast-house cooling (and thus lose water through evaporation), incomplete water monitoring (particularly of output water) and some of the "other uses" mentioned above. It accounts for 0.5 m^3 H_2O/t Al.

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[3] Sanitary uses, reported under "other uses" below and not precisely measured, involve negligible quantities of less than 0.1 m^3/t.

Other data

Sea water input and ***output*** (without consumption. i.e. output equals input) of 6.5 m^3/t Al, arises from the practice of wet scrubbing. This is undertaken by a limited number of smelters and entails diluting smelter air emissions (which are included in this study) into sea water to harmless concentrations, therefore involving significant quantities of input and discharged sea water[4].

Issues were identified in 2005 with ***polycyclic aromatic hydrocarbon*** and ***benzo-a-pyrene*** air emissions as figures were not consistent with industry experience and had been obtained under low (<20%) response rates. The improved 2010 response rate (50% for PAH, 35% for BaP) means that latest data, which demonstrate emissions 50% lower than the 2000-2005 level, can be considered more reliable. This reduction can also be partly ascribed to improvement in industry performance, primarily through a shift in the technology mix in the global and reporting industry towards increasing share of *Prebake* smelters (see next Section).

4.2 Changes reflecting "real" shifts

Comments in this section explore performance-driven differences between 2005 and 2010, organised by process. They 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.

4.2.1 Alumina Production

Bauxite consumption increased by around 6% in reported data between 2005 and 2010, reflecting a general and real trend of increasing demand being met by decreasing quality of ores.

Bauxite residue recycled fell by 70% over the same period, which is partly a function of demand increasing and ore quality declining faster than technologies to economically recycle bauxite residue are developing. One of the main users of recycled bauxite is the construction industry, which due to the recession has been in decline since 2008 and as such have been purchasing less bauxite. Bauxite residue recycled makes up less than 1% of the total residue that is produced, so although a 70% decrease seems large, the volumes involved are relatively small.

Bauxite residue deposited increased by 20%, a trend in line with the increased bauxite consumption noted above. As ore quality decreases there is a higher percentage of ore mass that remains post-extraction.

Differences in fuel mix between 2005 and 2010 data are summarised in the Table 4, which indicates a shift from oil and coal to natural gas in the reporting group. However, data from China, where coal predominates the fuel mix (>70% on a GJ/t Al_2O_3 basis), is not included in either the 2005 or 2010 datasets. Global IAI data,

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[4] Seawater consumption (0.4 m^3/t Al) arises from only one reported smelter desalination operation, which includes a proportion of local uses outside aluminium production.

which includes Chinese alumina industry fuel mix can be found at http://www.world-aluminium.org/statistics/metallurgical-alumina-refining-fuel-consumption/ and is illustrated in Figure 4.

		2010	2005
Heavy oil	kg/t Al2O3	83	101
Diesel oil	kg/t Al2O3	0.1	0.7
Natural Gas	m3/t Al2O3	139	116
Coal	kg/t Al2O3	74	89
Electricity	kWh/t Al2O3	79	126

Table 4: Life cycle inventory alumina industry fuel mix data for years 2005 and 2010

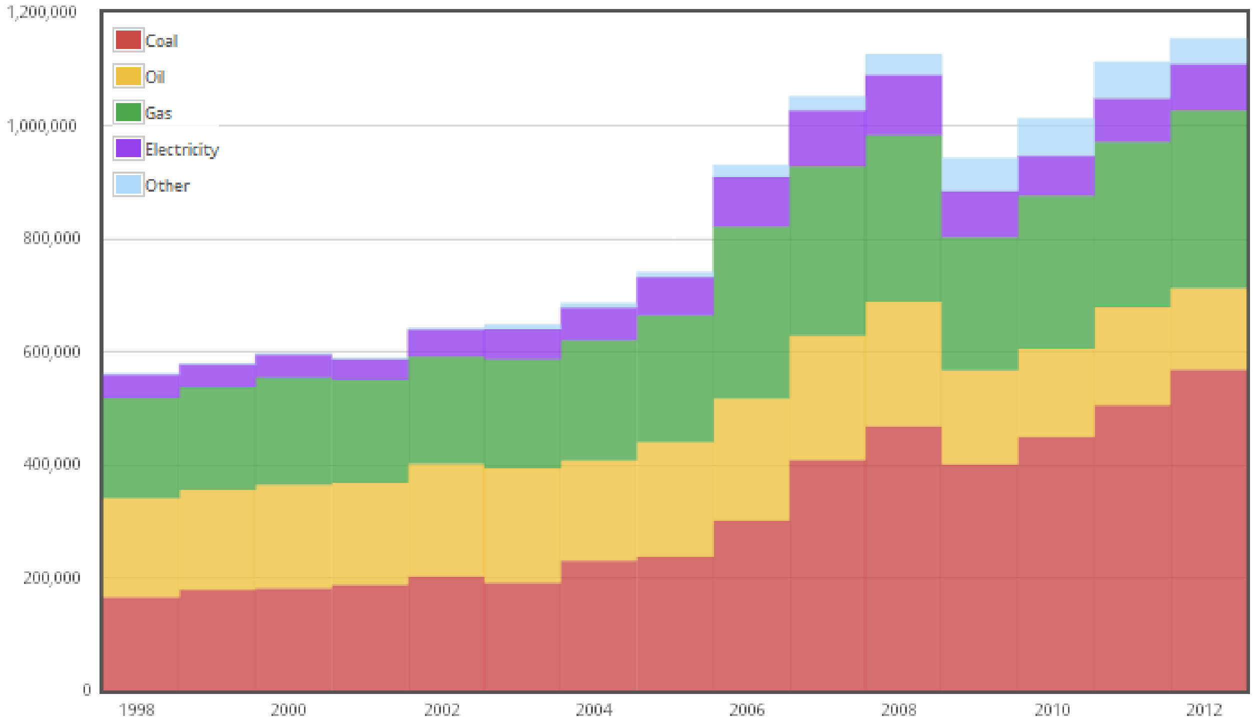


Figure 4: Global alumina industry fuel mix, 1998 – 2012 (www.world-aluminium.org/statistics)

Over the period 2005 to 2010, the global energy intensity of the alumina refining process (including China) has remained stable at around 14 GJ/t Al_2O_3, even as ore quality has been decreasing (Figure 5). This is due to significant technological efficiency improvements in newly installed capacity as well as the use of sweetening processes, wherein small quantities of higher quality bauxites are added to lower quality feed-stocks during high temperature digestion, boosting yield and lowering energy consumption.

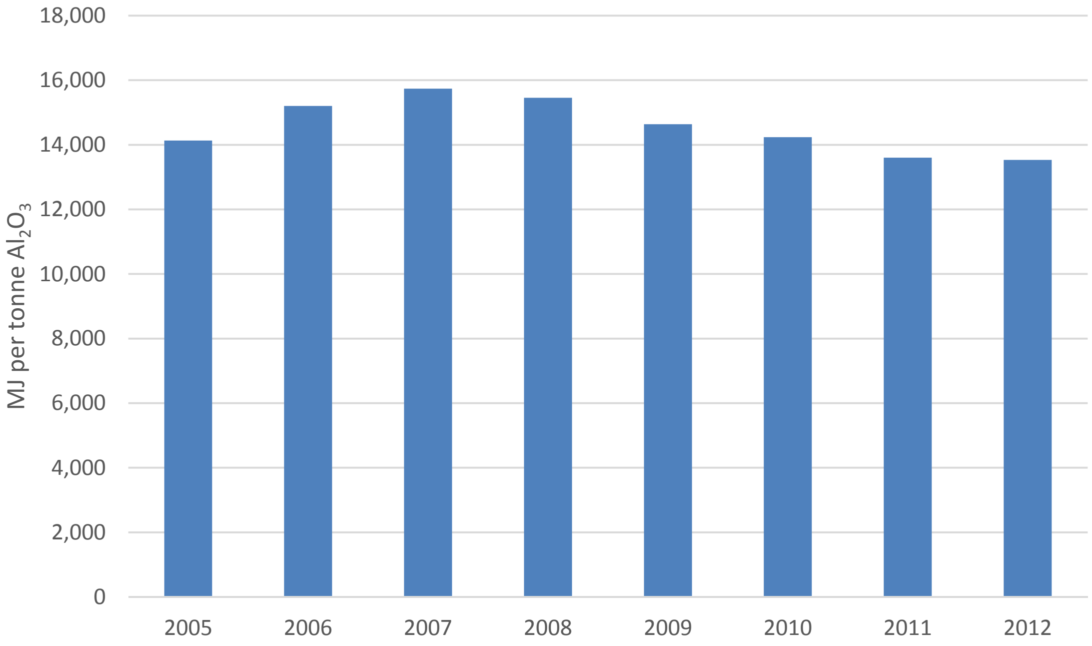


Figure 5: Global energy intensity of the alumina refining process for years 2005 – 2012 (www.world-aluminium.org/statistics)

4.2.2 Electrolysis

The perfluorocarbon gases ***tetrafluoromethane*** (CF_4) and ***hexafluoroethane*** (C_2F_6) were reduced by 34% and 47% respectively, reflecting an industry wide trend that saw total global perfluorocarbon emissions from the aluminium industry reduced by over 70% as CO_2e between 1990 and 2010 (over 90% on an intensity basis); a function of improved cell management in the 1990s and changing technology mix in the 2000s (Figure 6).

The IAI collects anode effect and perfluorocarbon emissions data on an annual basis and reports results for the global industry, including China. A global dataset from 1990 onwards can be found at http://www.world-aluminium.org/statistics/perflurocarbon-pfc/, with annual Anode Effect Survey Reports available from http://world-aluminium.org/publications/tagged/PFC/.

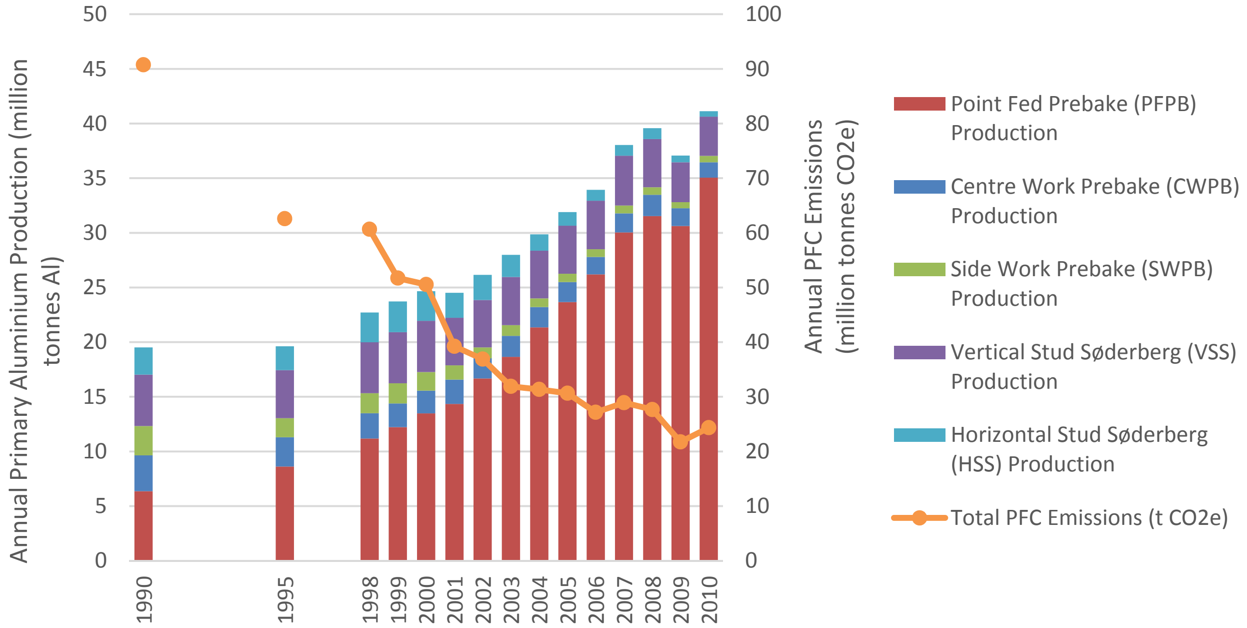


Figure 6: Total global aluminium industry perfluorocarbon emissions against global production

Reported ***particulate fluoride*** and ***gaseous fluoride*** remained relatively stable between 2005 and 2010. Fluorides emissions intensity was reduced by 50% between 1990 and 2010, again a function of technology changes and improvement in emissions management practices. A fluoride emissions dataset from 1990 for the global industry can be found at http://www.world-aluminium.org/statistics/smelter-fluoride-emissions/.

Spent Pot Lining (SPL) solid waste landfilled was reduced by 45% through improved recycling of the respective SPL-carbon and SPL-refractory fractions.

Stability in ***electricity*** consumption (15,289 kWh/t Al in 2005, 15,275 kWh/t Al in 2010) does not fully reflect the global industry, as neither dataset includes China. The majority of new production capacity installed over this period is located in China (a country acutely aware of energy constraints and focused on technology to improve energy efficiency), it is generally best available technology (and therefore more energy efficient than the average) and is found in larger facilities (which has a greater impact on production weighted averages).

Annual global data published by the IAI, which includes Chinese industry values, indicates a 2% reduction in smelting electrical energy intensity between 2005 and 2010, with a lower baseline (15,080 kWh/t Al) and final value (14,777 kWh/t Al). Such data can be found at http://world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/ and is illustrated in Figure 7.

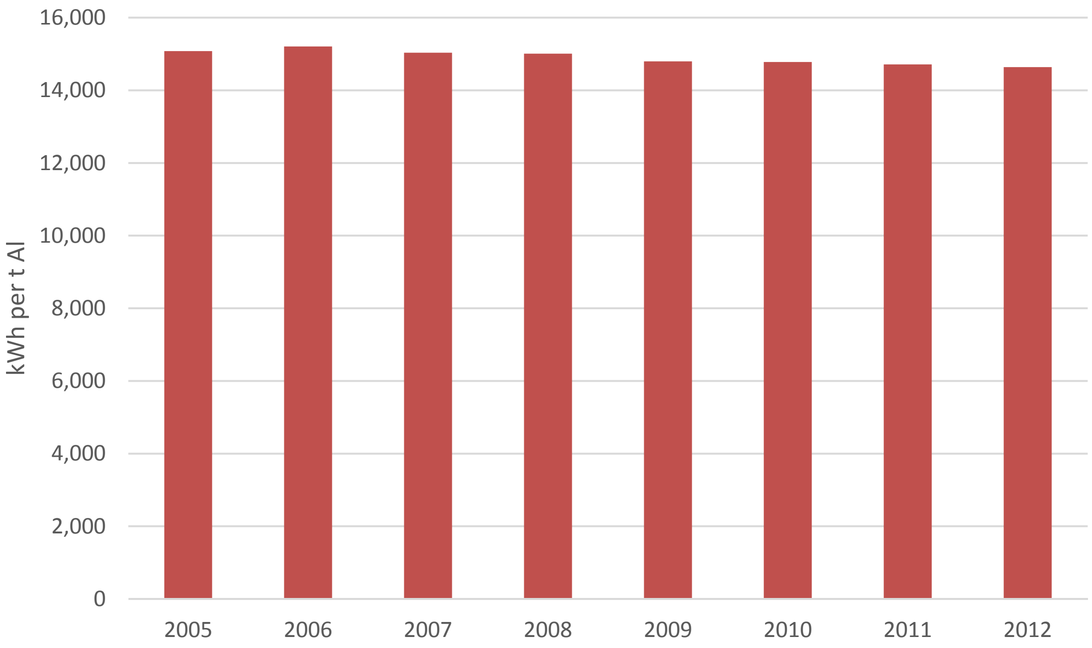


Figure 7: Global aluminium smelting electrical energy intensity for years 2005 – 2012 (www.world-aluminium.org/statistics)

5. Interpretation

Goal & Scope

The purpose of this inventory report is to characterize accurately and at the global level resource inputs and significant environmental releases associated with the production of primary aluminium.

This 2010 inventory can be considered the most accurate and up-to-date of any published global LCI on primary aluminium production.

With an increased focus on water use and on transport of materials the coverage of relevant inputs/outputs can be seen to have improved on the 2005 inventory. Third party review of the report has revealed areas for further exploration in the next iteration of LCI survey (2015), namely land use at each stage in the production process, but specifically in mining and refining and bauxite residue management and disposal.

Reported data (with industry responses to individual questions ranging from between 10 and 50% of the global industry) reveal relatively little change in the resource inputs and environmental outputs between the 2005 and 2010 surveys, the most significant being:

- an increase in bauxite consumption per tonne of product (a function of declining ore quality) and associated increase in bauxite residue volumes per tonne;
- further reduction in PFC emissions;
- shifts in fuel mix for alumina production towards gas from coal.

With respect to the inventory's characterization of the global industry's inputs and outputs, the greatest obstacle to achievement of this goal is the lack of Chinese industry data reported in a quality high enough for inclusion in the database.

The inventory includes no Chinese industry data, while the Chinese industry represents (in 2010) over 40% of global alumina and primary aluminium production. However, input-output data on the aluminium industry's processes tends to be more a function of technology in use than location (albeit that the background data, which in any case is out of the scope of this report, can be impacted significantly by the inclusion or exclusion of specific regions). Given that China employs 100% point fed prebake smelters and that its alumina refining technology is relatively similar in mix to the rest of the world, one could say that the data included herein is a reasonable approximation of the Chinese industry's inputs/outputs.

IAI published data indicates that Chinese smelting energy intensity is 5% lower on average than the rest of the world and refining energy 30% higher (in 2010).

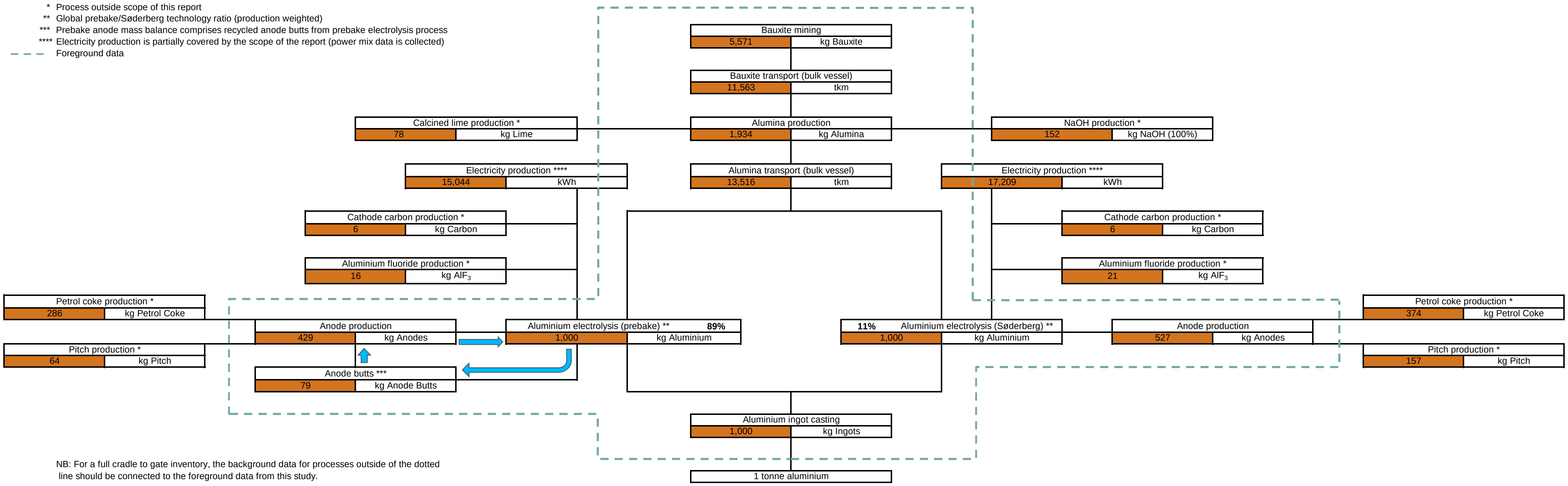
Having said that, China's power mix is more heavily coal based than the rest of the aluminium producing world – although such background data is outside the scope of this report. In this regard, users of this inventory data should ensure that they utilise aluminium industry specific power mix data, available from the IAI, rather than regional grid mixes. Alumina fuel mix is within the scope of this inventory however (although it is published by the IAI elsewhere) and here China does differ from the rest of the world; therefore one might say that this inventory more accurately characterises the Chinese aluminium industry (and thence global industry) than it does its alumina industry.

With China making up an increasing share of global production since 2010, future surveys will need to focus on obtaining more and better quality data from the Chinese industry, if future inventories are to continue to characterise accurately and at the global level resource inputs and significant environmental releases associated with the production of primary aluminium.

Appendix A: Unit process descriptions and inventory data

Excel versions of the inventory data can be downloaded from the World Aluminium website at the following link:
http://www.world-aluminium.org/publications/tagged/life%20cycle/

Unit Process Flow Chart



* Process outside scope of this report
** Global prebake/Søderberg technology ratio (production weighted)
*** Prebake anode mass balance comprises recycled anode butts from prebake electrolysis process
**** Electricity production is partially covered by the scope of the report (power mix data is collected)
– – – Foreground data

NB: For a full cradle to gate inventory, the background data for processes outside of the dotted line should be connected to the foreground data from this study.

Inputs and Outputs
(per tonne of product)

		Bauxite mining	Alumina production	Prebake anode production	Søderberg paste production	Prebake electrolysis	Søderberg electrolysis	Ingot casting
Reference Flow		*1 t bauxite*	*1 t alumina*	*1 t anodes*	*1 t paste*	*1 t liquid metal*	*1 t liquid metal*	*1 t ingots*
Transport								
Average sea transport	tkm		5,919			14,505	4,332	
Average road transport	tkm		4			6		
Average rail transport	tkm		56			98		
Material input								
Bauxite	kg/t		2,880.59					
Caustic soda	kg/t		78.56					
Calcined lime	kg/t		40.19					
Fresh water	m^3/t	0.50	2.57	1.09	4.54	3.89	3.89	3.49
Sea water	m^3/t	0.66	0.56			6.86	1.14	
Petrol coke	kg/t			666.94	708.89			
Pitch	kg/t			148.45	298.51			
Refractory material	kg/t			7.32		7.28	9.86	
Steel	kg/t			6.17		3.80	5.22	
Alumina (dry)	kg/t					1,935.38	1,923.76	
Anodes (net)/Søderberg Paste	kg/t					428.59	527.24	
Cathode carbon	kg/t					6.00	6.20	
Aluminium fluoride	kg/t					15.64	20.60	
Electrolysis metal	kg/t							1,000.00
Alloy additives	kg/t							19.57
Chlorine	kg/t							0.036
Energy input								
Heavy oil	kg/t	0.17	82.97	31.48	6.90			2.68
Diesel oil	kg/t	0.28	0.077	5.63	0.43			0.74
Natural gas	m^3/t		138.65	50.02	1.42			20.02
Coal	kg/t		73.73					0.96
Electricity	kWh/t	0.92	78.69	124.21	46.78	15,044.48	17,208.76	67.65
Air emissions								
Particulates	kg/t	0.17	0.56	0.21	0.10	1.94	7.70	0.037
of which < 2.5microns	kg/t		0.022	0.20		0.60	16.99	
Carbon dioxide from non-fuel combustion sources	kg/t			234.85		1,533.78	1,571.49	
Sulfur dioxide	kg/t		2.44	3.05	9.75	15.28	11.79	0.11
Nitrous oxides (as NO_2)	kg/t		0.68	0.56	1.51	0.26	0.16	0.072
Mercury	g/t		0.24					
Particulate fluoride (as F)	kg/t			0.0022		0.52	0.78	
Gaseous fluoride (as F)	kg/t			0.0077		0.50	1.19	
Total polycyclic aromatic hydrocarbons	kg/t			0.051	0.0075	0.0088	0.43	
Benzo(a)pyrene	g/t			0.22	0.012	0.11	6.03	
Tetrafluoromethane	kg/t					0.045	0.15	
Hexafluoroethane	kg/t					0.007	0.01	
Hydrogen chloride	kg/t							0.024
Dioxin/furans	kg/t							1.32E-09
Water emissions								
Fresh water	m^3/t	0.052	1.36	0.99	4.40	3.65	3.65	3.26
Sea water	m^3/t	0.66	0.56			6.37	1.14	
Suspended solids	kg/t		0.015	0.034	0.010	0.49	0.67	0.14
Oil and grease/total hydrocarbons	kg/t		0.77	0.0078		0.0036	0.017	0.037
Mercury	g/t		0.000068					
Fluoride (as F)	kg/t			0.0088		0.033	0.29	
Polycyclic aromatic hydrocarbons (6 Borneff components)	g/t			0.010	0.13	0.0073	2.43	
By-Products (for external recycling)								
Bauxite residue	kg/t		2.27					
Spent pot lining carbon	kg/t					10.08	4.81	
Spent pot lining refractory	kg/t					4.40	31.71	
Refractory	kg/t			4.79		2.76	0.42	0.73
Steel	kg/t			7.78		6.63	8.57	
Dross	kg/t							15.88
Filter dust	kg/t							1.49
Scrap sold	kg/t							4.41
Other	kg/t		5.60	10.02	0.19			
Solid waste (for landfilling)								
Mine solid waste	kg/t	0.062						
Bauxite residues (red mud)	kg/t		1,353.72					
Spent pot lining	kg/t					6.50	17.33	
Waste alumina	kg/t					4.21	4.63	
Waste carbon or mix	kg/t			17.13	6.63	4.62	17.90	
Scrubber sludges	kg/t			0.35		5.88	9.91	
Refractory (excl. spent pot lining)	kg/t			4.57		1.32	0.45	0.47
Dross	kg/t							5.27
Filter dust	kg/t							0.46
Other solid industrial waste	kg/t		17.57	4.15	1.51			0.56
of which landfill waste	kg/t		8.53					
of which hazardous waste	kg/t		9.30	2.75	1.36			
Calculated air emissions from fuel combustion								
Methane from fuels	kg/t	0.000055	0.034	0.0061	0.00092			0.0014
Nitrous oxide from fuels	kg/t	0.000011	0.0053	0.0011	0.00018			0.00020
Carbon dioxide from fuels	kg/t	1.38	695.60	208.00	25.14			54.03

Summary
(per tonne of aluminium ingot)

Tonnes of prebake anode per tonne of aluminium:	0.429	Prebake Al production:	36,773,145	Percentage Split:	89%
Tonnes of Søderberg paste per tonne of aluminium:	0.527	Søderberg Al Production:	4,375,595	Percentage Split:	11%

		Bauxite mining	Alumina production	Anode/Paste production	Electrolysis	Casting	Total
Reference Flow (Material		*Bauxite*	*Alumina*	*Anode/Paste*	*Liquid Metal*	*Ingot*	*1 t Ingot*
Reference Flow (Tonnes)		*5.571*	*1.934*	*0.439*	*1*	*1*	
Transport							
Average sea transport	tkm/t Al ingot		11,448		13,423		24,871
Average road transport	tkm/t Al ingot		7		6		13
Average rail transport	tkm/t Al ingot		108		87		195
Material input							
Bauxite	kg/t Al ingot		5,571.47				5,571.47
Caustic soda	kg/t Al ingot		151.94				151.94
Calcined lime	kg/t Al ingot		77.73				77.73
Fresh water	m^3/t Al ingot	2.77	4.98	0.67	3.89	3.49	15.80
Sea water	m^3/t Al ingot	3.69	1.08		6.25		11.02
Petrol coke	kg/t Al ingot			295.19			295.19
Pitch	kg/t Al ingot			73.59			73.59
Refractory material	kg/t Al ingot			2.80	7.56		10.36
Steel	kg/t Al ingot			2.36	3.95		6.31
Alumina (dry)	kg/t Al ingot				1,934.14		1,934.14
Anodes (net)/Søderberg Paste	kg/t Al ingot				439.08		439.08
Cathode carbon	kg/t Al ingot				6.02		6.02
Aluminium fluoride	kg/t Al ingot				16.17		16.17
Electrolysis metal	kg/t Al ingot					1,000.00	1,000.00
Alloy additives	kg/t Al ingot					19.57	19.57
Chlorine	kg/t Al ingot					0.036	0.036
Energy input							
Heavy oil	kg/t Al ingot	0.95	160.48	12.45		2.68	176.55
Diesel oil	kg/t Al ingot	1.56	0.15	2.18		0.74	4.63
Natural gas	m^3/t Al ingot		268.18	19.24		20.02	307.44
Coal	kg/t Al ingot		142.61			0.96	143.57
Electricity	kWh/t Al ingot	5.11	152.20	50.20	15,274.63	67.65	15,549.78
Air emissions							
Particulates	kg/t Al ingot	0.94	1.07	0.086	2.55	0.037	4.70
of which < 2.5microns	kg/t Al ingot		0.043	0.078	2.34		2.46
Carbon dioxide from non-fuel combustion sources	kg/t Al ingot			89.95	1,537.79		1,627.74
Sulfur dioxide	kg/t Al ingot		4.73	1.71	14.91	0.11	21.46
Nitrous oxides (as NO_2)	kg/t Al ingot		1.32	0.30	0.25	0.072	1.95
Mercury	g/t Al ingot		0.47				0.47
Particulate fluoride (as F)	kg/t Al ingot			0.00085	0.55		0.55
Gaseous fluoride (as F)	kg/t Al ingot			0.0029	0.57		0.58
Total polycyclic aromatic hydrocarbons	kg/t Al ingot			0.020	0.054		0.074
Benzo(a)pyrene	g/t Al ingot			0.084	0.74		0.82
Tetrafluoromethane	kg/t Al ingot				0.056		0.06
Hexafluoroethane	kg/t Al ingot				0.0075		0.01
Hydrogen chloride	kg/t Al ingot					0.024	0.024
Dioxin/furans	kg/t Al ingot					1.32E-09	1.32E-09
Water emissions							
Fresh water	m^3/t Al ingot	0.29	2.62	0.63	3.65	3.26	10.45
Sea water	m^3/t Al ingot	3.69	1.08		5.81		10.58
Suspended solids	kg/t Al ingot		0.029	0.013	0.51	0.14	0.69
Oil and grease/total hydrocarbons	kg/t Al ingot		1.50	0.0030	0.0050	0.037	1.54
Mercury	g/t Al ingot		0.00013				0.00013
Fluoride (as F)	kg/t Al ingot			0.0034	0.060		0.064
Polycyclic aromatic hydrocarbons (6 Borneff components)	g/t Al ingot			0.011	0.26		0.28
By-Products (for external recycling)							
Bauxite residue	kg/t Al ingot		4.39				4.39
Spent pot lining carbon	kg/t Al ingot				9.52		9.52
Spent pot lining refractory	kg/t Al ingot				7.30		7.30
Refractory	kg/t Al ingot			1.83	2.51	0.73	5.07
Steel	kg/t Al ingot			2.98	6.83		9.81
Dross	kg/t Al ingot					15.88	15.88
Filter dust	kg/t Al ingot					1.49	1.49
Scrap sold	kg/t Al ingot					4.41	4.41
Other	kg/t Al ingot		10.83	3.85			14.68
Solid waste (for landfilling)							
Mine solid waste	kg/t Al ingot	0.34					0.34
Bauxite residues (red mud)	kg/t Al ingot		2,618.29				2,618.29
Spent pot lining	kg/t Al ingot				7.65		7.65
Waste alumina	kg/t Al ingot				4.25		4.25
Waste carbon or mix	kg/t Al ingot			6.93	6.03		12.96
Scrubber sludges	kg/t Al ingot			0.13	6.31		6.44
Refractory (excl. spent pot lining)	kg/t Al ingot			1.75	1.23	0.47	3.44
Dross	kg/t Al ingot					5.27	5.27
Filter dust	kg/t Al ingot					0.46	0.46
Other solid industrial waste	kg/t Al ingot		33.98	1.67		0.56	36.22
of which landfill waste	kg/t Al ingot		16.50				16.50
of which hazardous waste	kg/t Al ingot		17.99	1.13			19.12
Calculated air emissions from fuel combustion							
Methane from fuels	kg/t Al ingot	0.00031	0.065	0.0024		0.0014	0.069
Nitrous oxide from fuels	kg/t Al ingot	0.000061	0.010	0.00041		0.00020	0.011
Carbon dioxide from fuels	kg/t Al ingot	7.71	1,345.38	81.08		54.03	1,488.20

Significant inventory inputs and outputs are reported in ***bold italic*** within the following unit process descriptions.

1. BAUXITE MINING

Inventory analysis unit process description

This unit process begins with the removal of overburden from a bauxite rich mining site. Reusable topsoil is normally stored for later mine site restoration.

The operations associated with this unit process include:
- the extraction of bauxite rich minerals from the site;
- beneficiation activities such as washing, screening, or drying;
- treatment of mining site residues and waste; and
- site restoration activities such as landscaping, topsoil replacement and replanting.

The output of this unit process is the ***bauxite*** that is transported to an alumina refinery.

Bauxite mining activities mainly take place in tropical and subtropical areas of the earth. Almost all bauxite is extracted using open pit mining methods. The known reserves of alumina containing ore will sustain the present rate of mining for over 100 years.

Commercial ***bauxite*** can be separated into ores composed of mostly alumina trihydrates and those composed of alumina monohydrates. The bauxite with trihydrate alumina contains approximately 50% alumina by weight, while monohydrates are approximately 30%. Monohydrates are normally found close to the surface (e.g. Australian ores), while trihydrates tend to be at deeper levels (e.g. Brazilian ores).

The only significant processing difference in bauxite mining is the need for beneficiation. Beneficiation is required with ores from forested areas, while the grassland type typically does not require washing. The ***waste water*** from washing is normally retained in a settling pond and recycled for continual reuse.

For further information on bauxite mining processes, refer to http://bauxite.world-aluminium.org/.

Bauxite Mining
(per tonne bauxite)

Global Production: 222,000,000 tonnes

	Unit	Value	Standard Deviation	Minimum	Maximum	Responding Production (t)	Response Rate
Material input							
Fresh water	m^3/t	0.50	0.89	3.99955E-05	2.66	110,322,419	50%
Sea water	m^3/t	0.66	n/a	n/a	n/a	13,138,076	6%
Energy input							
Heavy oil	kg/t	0.17	n/a	n/a	n/a	16,900,000	8%
Diesel oil	kg/t	0.28	1.65	0.23	3.47	42,892,343	19%
Electricity	kWh/t	0.92	7.31	0.04	15.73	61,815,693	28%
Air emissions							
Particulates	kg/t	0.17	0.25	0.01	0.54	82,332,095	37%
Water emissions							
Fresh water	m^3/t	0.05	0.09	0.00	0.22	76,734,229	35%
Sea water	m^3/t	0.66	n/a	n/a	n/a	13,138,076	6%
Solid waste (for landfilling)							
Mine solid waste	kg/t	0.06	0.03	0.002	0.09	96,729,170	44%

2. ALUMINA PRODUCTION

Inventory analysis unit process description

This unit process begins with unloading of process materials to their storage areas on site.

The operations associated with this unit process include:

- bauxite grinding, digestion and processing of liquors;
- alumina precipitation and calcination;
- maintenance and repair of plant and equipment; and
- treatment of process air, liquids and solids.

The output of this unit process is smelter grade ***alumina*** transported to an electrolysis plant (primary aluminium smelter).

In alumina production, also commonly named alumina refining, ***bauxite*** is converted to ***alumina*** (aluminium oxide) using the Bayer Process, which uses ***caustic soda*** and ***calcined lime*** *(limestone)* as input reactants. ***Bauxite*** is ground and blended into a liquor containing sodium carbonate and sodium hydroxide. The slurry is heated and pumped to digesters, which are heated pressure tanks. In digestion, iron and silicon impurities form insoluble oxides called ***bauxite residue***. The ***bauxite residue*** settles out and a rich concentration of sodium aluminate is filtered and seeded to form hydrate alumina crystals in precipitators. These crystals are then heated in a calcining process. The heat in the calciners drive off combined water, leaving alumina. ***Fresh water*** (surface and groundwater) or ***sea water*** is used as cooling agent.

The major differences in processing are at the calcination stage. Two types of kilns are used: rotary and fluid bed. The fluid bed or stationary kiln is newer and significantly more energy efficient. Energy requirements (***coal, diesel oil, heavy oil, natural gas, electricity***) have been halved over the last two decades with the introduction of higher pressure digesters and fluid flash calciners.

Air emissions mostly arise from the calcination stage *(**particulates**; **nitrous oxides (as NO_2)*** and ***sulfur dioxide*** from fuel combustion*; **mercury*** from the ore*),* while water emissions come from cooling use (***fresh water, sea water, oil and grease/total hydrocarbons***) or are linked with the digestion stage *(**suspended solids, mercury*** from the ore*).* Most of the ***bauxite residue (red mud)*** is currently deposited as solid waste, while a small but growing fraction is reused. ***Other*** (by-products for external recycling) are reaction chemicals. ***Other landfill wastes*** are typically inert components from ***bauxite*** such as sand, or waste chemicals.

For further information on alumina refining processes refer to http://bauxite.world-aluminium.org/.

For further information on the management of bauxite residue, please refer to http://www.world-aluminium.org/media/filer_public/2013/06/11/bauxite_residue_management_-_best_practice_1.pdf.

Alumina Production
(per tonne alumina)

Global Production: 85,000,000 tonnes

	Unit	Value	Standard Deviation	Minimum	Maximum	Responding Production (t)	Response Rate			
Transport										
Average sea transport	tkm	5,919	4,968	0	14,969	17,062,824	20%			
Average road transport	tkm	4	18	0	50	17,062,824	20%			
Average rail transport	tkm	56	106	0	319	17,062,824	20%			
Material input										
Bauxite	kg/t	2,881	598	1,874	3,587	25,010,877	29%			
Caustic soda	kg/t	78.56	29.57	47.40	132	21,092,287	25%			
Calcined lime	kg/t	40.19	13.77	16.20	61.06	26,457,859	31%			
Fresh water	m^3/t	2.57	7.60	0.29	33.29	30,127,816	35%			
Sea water	m^3/t	0.56	0.73	2.53	3.99	5,676,962	7%			
								Energy use per process:		
Energy input								*Hydrate production*	*Calcination*	
Heavy oil	kg/t	82.97	119	0.36	454	39,078,110	46%	*46.43*	*36.55*	
Diesel oil	kg/t	0.077	1.17	0.02	2.79	39,078,110	46%	*0.059*	*0.018*	
Natural gas	m^3/t	139	439	86.41	1,870	39,078,110	46%	*85.07*	*53.58*	
Coal	kg/t	73.73	560	126	1,532	39,078,110	46%	*73.69*	*0.04*	
Electricity	kWh/t	78.69	117	6.94	400	39,078,110	46%	*68.21*	*10.49*	
Air emissions										
Particulates	kg/t	0.56	1.01	0.07	4.20	28,783,481	34%			
of which < 2.5 microns	kg/t	0.022	0.009	0.01	0.03	12,302,229	14%			
Sulfur dioxide	kg/t	2.44	5.27	0.007	22.25	30,278,486	36%			
Nitrous oxides (as NO_2)	kg/t	0.68	0.78	0.02	3.17	30,272,140	36%			
Mercury	g/t	0.24	0.37	0.002	1.16	19,725,230	23%			
Water emissions										
Fresh water	m^3/t	1.36	7.90	0.00	32.14	28,783,481	34%			*(Cooling use 35%, from other uses - treated 45%, untreated 20%.)*
Sea water	m^3/t	0.56	0.73	2.53	3.98	5,676,962	7%			
Suspended solids	kg/t	0.015	173	2.56E-06	574	13,533,327	16%			
Oil and grease/total hydrocarbons	kg/t	0.77	0.75	0.04	1.50	4,202,526	5%			
Mercury	g/t	0.00007	0.07	1.03E-04	0.15	8,081,292	10%			
By-Products (for external recycling)										
Bauxite residue	kg/t	2.27	5.55	0.44	11.49	3,753,092	4%			
Other	kg/t	5.60	14.00	0.70	45.00	n/a	n/a			
Solid waste (for landfilling)										
Bauxite residues (red mud)	kg/t	1,354	592	392	2,147	31,284,496	37%			*(Treated deposition 21%, untreated deposition 79%)*
Other solid industrial waste	kg/t	17.57	47.83	1.10	182	26,734,318	31%			
of which landfill waste	kg/t	8.53	8.30	0.02	27.02	23,286,540	27%			
of which hazardous waste	kg/t	9.30	11.91	0.007	32.92	25,191,406	30%			

3. ANODE PRODUCTION

Inventory analysis unit process description
This unit process begins with the unloading of process materials to their storage areas on site. The operations associated with this unit process include: • recovery of spent anode materials; • anode mix preparation, anode block or briquette forming and baking; • rodding of baked anodes; • maintenance and repair of plant and equipment; and • treatment of process air, liquids and solids. The outputs of this unit process are rodded ***Prebake anodes*** or ***Søderberg paste*** briquettes transported to an electrolysis plant.

There are two types of aluminium smelting technologies that are distinguished by the type of anode that is used in the reduction process: *Søderberg* and *Prebake*.

Søderberg processes use a single anode, which covers most of the top surface of a reduction cell (pot). Anode paste in the form of carbon briquettes is fed to the top of the anode and as it is consumed in the electrolysis process, the paste moves downwards by gravity. Heat from the pot bakes the paste into a monolithic mass before it gets to the electrolytic bath interface.

Prebake processes use prefired blocks of solid carbon suspended from ***steel*** axial busbars, which hold the anodes in place and also conduct the current for electrolysis.

The process for making the aggregate for paste briquettes or pre-baked anodes is identical. ***Petrol coke*** is calcined, ground and blended with ***pitch*** to form a paste that is subsequently formed into blocks or briquettes and allowed to cool. While the briquettes are sent direct to the pots for consumption, the blocks are then sent to a separate baking furnace.

Baking furnace technology has evolved from simple pits that discharged volatiles directly to the atmosphere during the baking cycle to closed loop designs that convert the caloric heat of the volatile into a process fuel that reduces process energy consumption. Baking furnaces use ***refractory materials*** for linings and ***fresh water*** (surface and groundwater) as a cooling agent. Baking furnaces account for most of energy consumption (***coal, diesel oil, heavy oil, natural gas, electricity***) in the pre-baked anode production process.

Air emissions such as ***gaseous fluoride*** (***as F***) and ***particulate fluoride*** (***as F***) arise from the recycling of spent anode materials ("anode butts") recovered from electrolysis processes (see below). ***Particulates, nitrous oxides (as*** NO_2***)*** and ***sulfur dioxide*** emissions typically arise from fuel combustion. ***Total polycyclic aromatic hydrocarbons*** (PAH), which includes ***benzo-a-pyrene***, are air emissions generated from the basic anode production process.

Water emissions of ***fluoride*** (***as F***) and ***polycyclic aromatic hydrocarbons (6 Borneff components)*** are generated in the same way as their air emission equivalents above. The 6 Borneff components used as a marker for total PAH are: Fluoranthene, Benzo(k)fluoranthene, Benzo(b)fluoranthene, Indeno(1,2,3-cd)pyrene, Benzo(a)pyrene and Benzo(ghi)perylene. ***Suspended solids*** and ***oil and grease/total hydrocarbons*** are also monitored in water discharges.

The common practice for pollution control of anode baking furnaces is scrubbing with alumina and returning the alumina to the electrolysis process. In the case of separate anode baking plants this is replaced by coke and lime scrubbing, which is then returned to the process. For paste plants the common pollution prevention is coke scrubbing and returning the coke to the process. There are some plants still using water scrubbing, but this is not common and does not follow best practice. ***Fresh water*** emissions from paste and anode plants come from cooling processes.

By-products for external recycling includes used ***steel*** recovered from anode bars or used ***refractory material*** from baking furnaces. Various ***other*** by-products are also recovered, e.g. carbon recovered for re-use.

Solid waste(for landfilling): ***waste carbon or mix*** is a residue from anode production; ***scrubber sludges*** arising from water scrubbing used for control of air emissions mentioned above, and ***refractory*** waste from baking furnaces. **Other landfill wastes** arise as various residues, e.g. carbon fines.

For further information on anode production processes refer to http://primary.world-aluminium.org/.

Prebake Anode Production
(per tonne anode)

Global Production: 15,760,559 **tonnes** (calculated value)

	Unit	Value	Standard Deviation	Minimum	Maximum	Responding Production (t)	Response Rate
Material input							
Fresh water	m^3/t	1.09	1.43	0.06	10.05	3,376,322	21%
Petrol coke	kg/t	667	71.82	485	869	7,489,195	48%
Pitch	kg/t	148	9.89	131	171	7,489,195	48%
Refractory material	kg/t	7.32	7.53	0.06	28.51	3,789,255	24%
Steel	kg/t	6.17	4.44	0.25	15.08	1,625,817	10%
Energy input							
Heavy oil	kg/t	31.48	83.06	33.05	290	6,574,033	42%
Diesel oil	kg/t	5.63	25.49	0.08	57.12	6,574,033	42%
Natural gas	m^3/t	50.02	26.52	6.35	139.03	6,574,033	42%
Electricity	kWh/t	124	58.35	0.13	239.44	6,574,033	42%
Air emissions							
Particulates	kg/t	0.21	0.20	0.009	0.77	4,334,130	27%
of which < 2.5microns	kg/t	0.20	0.22	0.01	0.53	1,238,120	8%
Carbon dioxide from non-fuel combustion sources	kg/t	235	n/a	n/a	n/a	n/a	n/a
Sulfur dioxide	kg/t	3.05	7.99	0.01	39.73	4,609,995	29%
Nitrous oxides (as NO_2)	kg/t	0.56	0.65	0.05	2.90	3,454,565	22%
Particulate fluoride (as F)	kg/t	0.002	0.003	1.81E-05	0.01	2,808,558	18%
Gaseous fluoride (as F)	kg/t	0.008	0.01	7.23E-05	0.05	4,714,320	30%
Total polycyclic aromatic hydrocarbons	kg/t	0.05	0.12	1.06E-03	0.42	3,613,541	23%
Benzo(a)pyrene	g/t	0.22	0.93	6.53E-04	3.26	2,325,653	15%
Water emissions							
Fresh water	m^3/t	0.99	1.26	0.00	3.36	2,648,621	17%
Suspended solids	kg/t	0.03	0.006	0.00	0.02	941,680	6%
Oil and grease/total hydrocarbons	kg/t	0.008	0.01	0.00	0.02	999,668	6%
Fluoride (as F)	kg/t	0.009	0.01	0.00	0.03	847,912	5%
Polycyclic aromatic hydrocarbons (6 Borneff components)	g/t	0.01	0.03	0.00	0.08	849,653	5%
By-Products (for external recycling)							
Refractory	kg/t	4.79	6.25	3.05	22.51	2,797,500	18%
Steel	kg/t	7.78	8.20	0.54	24.12	3,215,651	20%
Other	kg/t	10.02	15.91	0.90	47.65	2,163,013	14%
Solid waste (for landfilling)							
Waste carbon or mix	kg/t	17.13	17.25	1.51	66.07	4,392,361	28%
Scrubber sludges	kg/t	0.35	1.47	0.01	2.58	995,573	6%
Refractory (excl. spent pot lining)	kg/t	4.57	5.08	0.10	12.57	2,340,014	15%
Other solid industrial waste	kg/t	4.15	7.56	0.00	21.71	3,406,739	22%
...of which hazardous waste	kg/t	2.75	6.43	0.00	22.62	3,339,263	21%

Søderberg Paste Production
(per tonne paste)

Global Production: 2,306,971 **tonnes** (calculated value)

	Unit	Value	Standard Deviation	Minimum	Maximum	Responding Production (t)	Response Rate
Material input							
Fresh water	m^3/t	4.54	3.99	0.85	11.34	138,758	6%
Petrol coke	kg/t	709	31.39	681	771	2,127,573	92%
Pitch	kg/t	299	27.59	229	327	2,127,573	92%
Energy input							
Heavy oil	kg/t	6.90	13.74	1.69	39.09	2,155,970	93%
Diesel oil	kg/t	0.43	n/a	n/a	n/a	2,155,970	93%
Natural gas	m^3/t	1.42	2.89	11.29	15.38	2,155,970	93%
Electricity	kWh/t	46.78	43.79	12.27	169	2,155,970	93%
Air emissions							
Particulates	kg/t	0.10	0.24	0.00	0.62	300,035	13%
Sulfur dioxide	kg/t	9.75	9.78	0.01	21.93	212,847	9%
Nitrous oxides (as NO_2)	kg/t	1.51	1.29	0.03	2.64	165,878	7%
Total polycyclic aromatic hydrocarbons	kg/t	0.007	0.01	9.87E-06	0.02	158,884	7%
Benzo(a)pyrene	g/t	0.01	0.02	1.42E-08	0.03	114,061	5%
Water emissions							
Fresh water	m^3/t	4.40	1.98	0.85	5.84	138,758	6%
Suspended solids	kg/t	0.01	n/a	n/a	n/a	46,970	2%
Polycyclic aromatic hydrocarbons (6 Borneff components)	g/t	0.13	n/a	n/a	n/a	44,823	2%
By-Products (for external recycling)							
Other	kg/t	0.19	n/a	n/a	n/a	44,665	2%
Solid waste (for landfilling)							
Waste carbon or mix	kg/t	6.63	4.83	0.60	10.95	255,370	11%
Other solid industrial waste	kg/t	1.51	2.42	0.00	5.14	170,348	7%
of which hazardous waste	kg/t	1.36	3.27	0.00	4.62	31,501	1%

4. ELECTROLYSIS

Inventory analysis unit process description
This unit process begins with the unloading of process materials to their storage areas on site. The operations associated with this unit process include: • recovery, preparation and handling of process materials; • manufacture of major process equipment (e.g. cathodes); • process control activities (metal, bath, heat); • maintenance and repair of plant and equipment; and • treatment of process air, liquids and solids. The output of this unit process is ***electrolysis metal*** transported to an ingot casting facility.

The electrolysis process is also commonly known as “reduction” or, together with anode production, “aluminium smelting”.

Molten aluminium is produced from ***alumina*** through the Hall-Héroult electrolytic process that sees the ***alumina*** dissolved in a molten cryolite (***aluminium fluoride***) “bath” and a direct electric current passed through the solution, thereby decomposing the ***alumina*** into ***aluminium*** and oxygen. Aluminium is tapped from the reduction cell (pot) at daily intervals and the oxygen combines with the carbon of the anode to form ***carbon dioxide (non-fuel combustion source)***.

The pot consists of a ***steel*** shell lined with ***refractory materials*** insulation and with a hearth of ***cathode carbon***. The cathode is filled with a cryolite bath and ***alumina*** and an anode is suspended in the bath to complete the circuit for the pot. Once started, a pot will run continuously for the life of the cathode, which may last for in excess of 10 years. At the end of its life each pot is completely refurbished. ***Steel*** from used cathodes is recovered for recycling. ***Refractory materials*** are either recycled as by-products or landfilled (***refractory waste – landfill***). Spent pot linings (SPL), which include a carbon-based and a refractory-based part are either recycled as by-products or landfilled.

The electrical current through a pot varies from 60 to over 500 kiloamperes (kA) at a voltage range of 4.2 to 5.0 volts, depending on cell design. Pots produce around 7 to 7.5 kg of aluminium per kA per day at an operating efficiency of 85 to 95%. ***Electricity*** is the dominant energy source consumed during electrolysis.

Aluminium smelters typically employ air pollution control systems to reduce emissions to the atmosphere. The primary system is typically a scrubber. Many plants use dry scrubbers with ***alumina*** as an adsorbent that is subsequently fed to the pots and allows for the recovery of scrubbed materials. Other plants use wet scrubbers, which recirculate an alkaline solution to adsorb gases: the wet scrubbing process uses ***fresh water*** (surface and groundwater) or ***sea water*** as input and results in corresponding ***fresh water*** or ***sea water*** discharges. Unlike dry scrubbers, wet scrubbers adsorb carbon dioxide, nitrogen oxide and sulphur dioxide that are entrained in the waste water liquor (which is subsequently treated prior to final discharge). ***Scrubber sludges*** are landfilled.

Specific aluminium electrolysis process air emissions are ***gaseous fluoride (as F)***, ***particulate fluoride (as F)***, which arise from the molten bath; ***total polycyclic aromatic hydrocarbons***, which includes ***benzo-a-pyrene***, which arise from anode consumption. ***Tetrafluoromethane*** and ***Hexafluoroethane***, commonly reported as perfluorocarbons or PFCs, are gases usually generated through an uncontrolled anode voltage excursion known as an “anode effect”. ***Particulates, nitrous oxides (as NO_2)*** and ***sulfur dioxide*** emissions typically arise from fuel combustion.

Water emissions of ***fluoride*** (***as F***) and ***polycyclic aromatic hydrocarbons (6 Borneff components)*** are generated in the same way as their air emission equivalents above. The 6 Borneff components used as a marker for total PAH are: Fluoranthene, Benzo(k)fluoranthene, Benzo(b)fluoranthene, Indeno(1,2,3-cd)pyrene, Benzo(a)pyrene and Benzo(ghi)perylene. ***Suspended solids*** and ***oil and grease/total hydrocarbons*** are also monitored in water discharges.

Solid waste: ***other landfill wastes*** typically consist of around 60% "environmental abatement" wastes (such as dry scrubber filter bags) and 40% "municipal" wastes (Aluminum Association, 1998).

For further information on electrolytic processes refer to http://primary.world-aluminium.org.

Prebake Electrolysis
(per tonne aluminium)

Global Production: 36,773,145 **tonnes**

	Unit	Value	Standard Deviation	Minimum	Maximum	Responding Production (t)	Response Rate
Transport							
Average sea transport	tkm	14,505	8,165	2867	28,869	5,145,771	14%
Average road transport	tkm	6	10	0	38	5,145,771	14%
Average rail transport	tkm	98	547	0	1,723	5,145,771	14%
Material input							
Fresh water	m^3/t	3.89	24.42	0.17	89.07	8,218,218	22%
Sea water	m^3/t	6.86	120	6.19	237	1,396,625	4%
Refractory material	kg/t	7.28	6.99	0.80	28.34	6,250,990	17%
Steel	kg/t	3.80	2.69	0.03	9.64	6,621,753	18%
Alumina (dry)	kg/t	1,935	72.96	1,891	2,322	10,325,162	28%
Anodes (net)/Søderberg Paste	kg/t	429	40.77	297	583	14,389,691	39%
Cathode carbon	kg/t	6.00	3.10	0.00	11.18	6,959,240	19%
Aluminium fluoride	kg/t	15.64	3.64	9.68	28.18	10,325,162	28%
Energy input							
Electricity	kWh/t	15,044	1,179	13,504	20,592	15,338,788	42%
Air emissions							
Particulates	kg/t	1.94	2.65	0.01	12.70	10,366,405	28%
of which < 2.5microns	kg/t	0.60	0.39	0.03	1.05	1,354,470	4%
Carbon dioxide from non-fuel combustion sources	kg/t	1,534	n/a	n/a	n/a	n/a	n/a
Sulfur dioxide	kg/t	15.28	5.70	0.55	22.29	10,539,368	29%
Nitrous oxides (as NO_2)	kg/t	0.26	0.63	1.49E-03	2.92	6,589,660	18%
Particulate fluoride (as F)	kg/t	0.52	0.73	6.14E-06	3.38	10,317,607	28%
Gaseous fluoride (as F)	kg/t	0.50	0.66	0.03	4.18	10,730,560	29%
Total polycyclic aromatic hydrocarbons	kg/t	0.009	0.02	1.92E-04	0.08	4,893,731	13%
Benzo(a)pyrene	g/t	0.11	0.58	1.01E-03	1.84	2,915,951	8%
Tetrafluoromethane	kg/t	0.05	n/a	n/a	n/a	20,913,347	57%
Hexafluoroethane	kg/t	0.007	n/a	n/a	n/a	20,913,347	57%
Water emissions							
Fresh water	m^3/t	3.65	24.34	0.07	87.83	7,375,651	20%
Sea water	m^3/t	6.37	121	0.00	237	1,396,625	4%
Suspended solids	kg/t	0.49	1.99	8.19E-04	9.38	6,327,900	17%
Oil and grease/total hydrocarbons	kg/t	0.004	0.004	7.99E-05	0.01	2,421,611	7%
Fluoride (as F)	kg/t	0.03	0.14	5.93E-05	0.67	6,092,454	17%
Polycyclic aromatic hydrocarbons (6 Borneff components)	g/t	0.007	0.02	3.93E-05	0.06	2,256,855	6%
By-Products (for external recycling)							
Spent pot lining carbon	kg/t	10.08	6.44	0.00	20.27	8,818,995	24%
Spent pot lining refractory	kg/t	4.40	7.16	0.00	21.77	8,818,995	24%
Refractory	kg/t	2.76	52.15	0.08	105	1,004,882	3%
Steel	kg/t	6.63	4.62	0.86	13.66	4,199,396	11%
Solid waste (for landfiling)							
Spent pot lining	kg/t	6.50	12.00	0.00	52.27	9,791,197	27%
Waste alumina	kg/t	4.21	14.18	0.00	57.61	4,485,381	12%
Waste carbon or mix	kg/t	4.62	6.36	0.00	17.46	6,403,207	17%
Scrubber sludges	kg/t	5.88	17.27	0.00	46.58	2,498,498	7%
Refractory (excl. spent pot lining)	kg/t	1.32	4.02	0.00	10.87	5,161,441	14%

Søderberg Electrolysis
(per tonne aluminium)

Global Production: 4,375,595 **tonnes**

	Unit	Value	Standard Deviation	Minimum	Maximum	Responding Production (t)	Response Rate
Transport							
Average sea transport	tkm	4,332	6,855	0	15,441	323,549	7%
Material input							
Fresh water	m^3/t	3.89	24.42	0.17	89.07	337,356	8%
Sea water	m^3/t	1.14	n/a	n/a	n/a	184,366	4%
Refractory material	kg/t	9.86	8.87	1.87	19.60	230,136	5%
Steel	kg/t	5.22	2.01	1.93	6.71	323,549	7%
Alumina (dry)	kg/t	1,924	23.42	1,878	1,950	471,869	11%
Anodes (net)/Søderberg Paste	kg/t	527	31.22	467	622	3,766,529	86%
Cathode carbon	kg/t	6.20	4.82	0.00	9.95	323,549	7%
Aluminium fluoride	kg/t	20.60	7.27	12.81	32.35	656,235	15%
Energy input							
Electricity	kWh/t	17,209	1,233	15,163	20,043	4,089,195	93%
Air emissions							
Particulates	kg/t	7.70	8.30	1.24	22.45	656,235	15%
of which < 2.5microns	kg/t	16.99	n/a	16.99	16.99	99,652	2%
Carbon dioxide from non-fuel combustion sources	kg/t	1,571	n/a	n/a	n/a	n/a	n/a
Sulfur dioxide	kg/t	11.79	8.77	0.11	22.79	607,567	14%
Nitrous oxides (as NO_2)	kg/t	0.16	0.21	0.01	0.50	358,008	8%
Particulate fluoride (as F)	kg/t	0.78	0.74	0.24	2.11	651,565	15%
Gaseous fluoride (as F)	kg/t	1.19	0.81	0.06	2.56	656,235	15%
Total polycyclic aromatic hydrocarbons	kg/t	0.43	0.22	0.004	0.65	607,567	14%
Benzo(a)pyrene	g/t	6.03	3.93	0.03	10.64	602,897	14%
Tetrafluoromethane	kg/t	0.15	n/a	n/a	n/a	4,081,894	93%
Hexafluoroethane	kg/t	0.01	n/a	n/a	n/a	4,081,894	93%
Water emissions							
Fresh water	m^3/t	3.65	24.34	0.07	87.83	425,684	10%
Sea water	m^3/t	1.14	n/a	n/a	n/a	184,366	4%
Suspended solids	kg/t	0.67	1.30	0.02	3.09	522,668	12%
Oil and grease/total hydrocarbons	kg/t	0.017	3.18E-04	0.02	0.02	149,907	3%
Fluoride (as F)	kg/t	0.29	0.49	0.01	1.16	522,668	12%
Polycyclic aromatic hydrocarbons (6 Borneff components)	g/t	2.43	5.03	0.05	8.88	334,688	8%
By-Products (for external recycling)							
Spent pot lining carbon	kg/t	4.81	5.37	0.00	10.06	294,798	7%
Spent pot lining refractory	kg/t	31.71	25.63	0.00	45.72	294,798	7%
Refractory	kg/t	0.42	2.06	0.02	4.05	198,575	5%
Steel	kg/t	8.57	5.37	3.72	16.44	287,318	7%
Solid waste (for landfiling)							
Spent pot lining	kg/t	17.33	16.67	0.00	38.29	656,235	15%
Waste alumina	kg/t	4.63	4.79	0.08	10.59	318,879	7%
Waste carbon or mix	kg/t	17.90	17.13	4.24	42.18	503,245	12%
Scrubber sludges	kg/t	9.91	19.60	0.32	39.99	203,660	5%
Refractory (excl. spent pot lining)	kg/t	0.45	0.65	0.00	1.31	234,806	5%

5. INGOT CASTING

Inventory analysis unit process description

This unit process begins with the unloading of process materials to their storage areas on site.

The operations associated with this unit process include:

- pre-treatment of hot metal (cleaning and auxiliary heating);
- recovery and handling of internal process scrap;
- batching, metal treatment and casting operations;
- homogenizing, sawing and packaging activities;
- maintenance and repair of plant and equipment; and
- treatment of process air, liquids and solids.

The output of this unit process is packaged aluminium ingots or alloyed hot metal transported to an aluminium fabricating facility.

Molten ***electrolysis metal*** siphoned from the pots is sent to a resident casting complex found in each smelter. In some cases, due to proximity, molten metal is transported directly to a shape casting foundry. ***Remelt ingot*** and ***outside scrap*** may also be used as metal input. Molten metal is transferred to a holding furnace and the composition is adjusted to the specific alloy requested by a customer, by use of ***alloy additives***. In some instances, depending on the application and on the bath composition in the pots, some initial hot metal treatment to remove impurities may be done.

When the alloying is complete, the melt is stirred and sometimes fluxed with flushing gases to remove impurities and reduce gas content. As a result, the liquid metal in the furnace is covered by a layer consisting of liquid aluminium, aluminium oxide skins and gas bubbles, (typically called ***dross***) which is skimmed off. The dross is normally further processed, primarily to recover the aluminium content.

Depending on the application, the metal is processed through an inline degasser combined with an inline filter to remove impurities (mainly hydrogen, sodium and non-metal inclusions). For inline degassing, flushing gases typically consist of nitrogen or argon with the addition of chlorine. Metal is then cast into ingots in a variety of methods: open moulds (typically for ***remelt ingot***), through direct chill moulds for various fabrication shapes, electromagnetic moulds for some sheet ingots, and through continuous casters for aluminium coils. ***Fresh water*** (surface or groundwater) is used for cooling (often with re-circulation through a cooling tower and water treatment plant) and is subsequently discharged, where ***suspended solids*** and ***oil and grease/total hydrocarbons***) are monitored.

Energy carriers for ingot casting are ***electricity***, ***natural gas*** or ***heavy oil***. ***Diesel oil*** is normally used for internal plant transport.

While recovery and handling of internal process scrap is usually included in the ingot casting operation as mentioned above, some casthouses prefer to sell it to independent recyclers (***scrap sold*** as by-product for external recycling). ***Dross***, ***filter dust*** from melting furnace air filtration and ***refractory*** material from furnace internal linings are either recovered as by-products for external recycling, or landfilled.

Solid waste: ***other landfill wastes*** typically consist of around 80% "environmental abatement" wastes (such as metal filter box and baghouse filters) and 20% "municipal" wastes (Aluminum Association, 1998).

Particulates, nitrous oxides (as NO_2***)*** and ***sulfur dioxide*** emissions typically arise from fuel combustion.

For further information on aluminium casting processes refer to http://primary.world-aluminium.org.

Ingot Casting
(per tonne aluminium ingot)

Global Production: 40,000,000 tonnes

	Unit	Value	Standard Deviation	Minimum	Maximum	Responding Production (t)	Response Rate
Material input							
Fresh water	m^3/t	3.49	8.95	0.10	31.98	4,198,681	10%
Electrolysis metal	kg/t	1,000	n/a	n/a	n/a	n/a	n/a
Alloy additives	kg/t	19.57	13.62	0.83	68.22	8,277,052	21%
Chlorine	kg/t	0.04	0.06	1.77E-04	0.15	3,103,598	8%
Energy input							
Heavy oil	kg/t	2.68	14.69	0.12	46.39	15,987,978	40%
Diesel oil	kg/t	0.74	8.91	0.30	24.97	15,987,978	40%
Natural gas	m^3/t	20.02	63.17	0.00	413	15,987,978	40%
Coal	kg/t	0.96	23.88	17.18	50.95	15,987,978	40%
Electricity	kWh/t	67.65	298	0.05	2,310	15,987,978	40%
Air emissions							
Particulates	kg/t	0.04	0.06	3.96E-03	0.32	5,112,972	13%
Sulfur dioxide	kg/t	0.11	0.22	1.01E-04	0.67	3,294,691	8%
Nitrous oxides (as NO_2)	kg/t	0.07	0.099	0.006	0.51	4,846,207	12%
Hydrogen chloride	kg/t	0.02	0.03	9.11E-06	0.11	2,341,811	6%
Dioxin/furans	kg/t	1.32E-09	4.68E-09	4.56E-13	1.16E-08	1,124,087	3%
Water emissions							
Fresh water	m^3/t	3.26	8.86	0.00	30.53	4,198,681	10%
Suspended solids	kg/t	0.14	0.68	0.001	1.95	1,109,802	3%
Oil and grease/total hydrocarbons	kg/t	0.04	0.09	2.78E-04	0.25	1,828,067	5%
By-Products (for external recycling)							
Refractory	kg/t	0.73	0.93	0.06	2.79	1,353,348	3%
Dross	kg/t	15.88	11.85	1.50	76.50	8,979,410	22%
Filter dust	kg/t	1.49	1.04	0.06	2.15	1,015,361	3%
Scrap sold	kg/t	4.41	8.70	0.00	27.93	3,793,477	9%
Solid waste (for landfiling)							
Refractory (excl. spent pot lining)	kg/t	0.47	0.71	0.00	2.39	5,057,824	13%
Dross	kg/t	5.27	6.25	0.00	24.07	5,069,494	13%
Filter dust	kg/t	0.46	0.45	0.00	1.50	2,124,501	5%
Other solid industrial waste	kg/t	0.56	3.51	0.00	12.70	4,167,444	10%

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Appendix C: Reviewers comments

Global Life Cycle Assessment Inventory Data for the primary Aluminium Industry

2010 Data

Final Report

August 2013

Critical Review Report

by

Walter Klöpffer

Frankfurt/M

and

Rolf Frischknecht

Zürich

August 2013

Preface

This critical review report is the final step of a review process which started 1st May 2012 after some preliminary discussions, confidentiality agreement and offer. The first critical review report (June 2012) was based on Draft 2 by IAI (March 2012), written by Bernard de Gélas (Paris) in the format used by previous data reports, the most recent one dealing with year 2005 update. The critical review requested major revisions both in the structure of the text and the data quality and presentation. The writing of the year 2010 report was now taken over by the IAI headquarter in London. The format was improved to give a better readability for the global audience. This needed some time. Data approved by the critical review – before the final report was ready – could be delivered to the European Aluminium Association (EAA, Brussels) in March/April 2013. This data was needed for the 2010 update of the European Aluminium LCA report [EAA 2013]. As in the case of the global reports by IAI, the European reports are updated every five years [Leroy 2009].

This critical review is based on the “Final 2010 Data report” (August 2013). The final report was preceded by Draft 6 (May 2013, received 06.06.2013), and has been discussed in detail in written form and during a face-to-face meeting July 24 in London. The present critical review report consists of two parts:

Part 1, written by Walter Klöpffer, deals with the ISO-aspects of the Life Cycle Inventory report [ISO 2006a,b]. Since the data will be used for Life Cycle Assessment (LCA) and similar studies, the reporting should follow the rules given by the international standards cited.

Part 2, written by Rolf Frischknecht, deals with the important questions related to the data: coverage, averaging, collecting and other quality-related items. Of course, the two parts cannot and should not be fully separated.

Part 1: The Life Cycle Inventory study according to ISO 14040 + 14044

1 Formal criteria

From a formal (ISO 14040+44) point of view, this report constitutes an LCI study report which should cover the phases

- Goal and Scope definition (G&S)
- Life Cycle Inventory analysis (LCI), and
- Interpretation

In contrast to a full LCA report, the phase Life Cycle Impact Assessment (LCIA) is excluded. Therefore, no conclusions about environmental impacts can be drawn from an LCI study; the report of the phase “Interpretation” can be shorter than in a full LCA study. For the same reason, no results “intended to be used to support a comparative assertion intended to be disclosed to the public” [ISO 2006b] can be obtained from such a study. Furthermore, the critical review can be performed by one or more independent experts, no “review by interested parties” is necessary.

2 Requirements to be met by a LCA/LCI study

For the critical review of a full LCA study, the international standard states the following requirements.

"The critical review process shall ensure that:

- *the methods used to carry out the LCA are consistent with this International Standard;*
- *the methods used to carry out the LCA are scientifically and technically valid;*
- *the data used are appropriate and reasonable in relation to the goal of the study;*
- *the interpretations reflect the limitations identified and the goal of the study; and*
- *the study report is transparent and consistent."*

This list can also be used for an LCI study, although not all items have the same weight due to the absence of the Life Cycle Impact Assessment phase.

2.1 Consistency with the standard

A first impression about the consistency is given by the structure of the report. In this regard, a clear chapter 1 on Goal & Scope describes the system boundaries (the graphical presentation is found in appendix A) and presents other important information about the system studied. Chapters 2 to 4 deal with data collection, analysis and trends and differences compared with 2005. These chapters together can be accepted as "Life Cycle Inventory analysis", the second phase of an LCI study. A short chapter 5 (Interpretation) is rounding up the structure,

More important than the purely formal coincidence, there seem to be no major deviations from life cycle assessment, as defined by the international standards. The coincidence with the standards is therefore given.

2.2 Scientific and technical validity of the methods used

The methods used correspond to the present state of the art. The problems surfacing here and there in this study are due to missing data (see below), not to the inability to handle them. Given the enormous scope of the study (theoretically the whole industrialised world!) the methodological frame is excellent. The processes are well described and the science and technology behind are presented in a concise way.

2.3 Data in relation to the goal of the study

For details on data see Part 2.

Here, only two groups of missing data should be mentioned:

- The existing data for China have not the necessary quality to be used in this report. Since China produces 40% of the primary aluminium worldwide, the data could be much more representative.
- The processes near the "cradle" – bauxite mining and alumina production – are incomplete with regard to land use. This includes the handling of the bauxite residues ("red mud"). Since the impact category Land use is gaining importance within the phase LCIA (in full LCA studies), aluminium cannot be treated adequately. This deficiency has already been criticized with regard to the European 2005 data report [Klöpffer 2009], depending on the global data for bauxite and alumina.

2.4 Interpretation of limitations with regard to the goal of the study

The limitations of the study are discussed at many occasions, also with regard to processes outside the system boundaries (to be included by the users of the study from other data sources). There is also a short chapter 5 "Interpretation" in which also the deficiencies mentioned in section 2.3 are added as points to be improved in the next update (2015 data).

2.5 Transparency and consistency of the Report

The report is well written and transparent. The style is concise, the illustrations in colour. No major inconsistencies have been detected.

With regard to data presentation see Part 2.

The (environmental) image of aluminium has been much improved by using life cycle thinking and assessment in recent years. The provision and frequent update of reliable data plays a major role in this process and should be continued.

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Part 2: The Life Cycle Inventory data according to ISO 14040 + 14044

1 Introduction

This Part 2 focuses on the review of the LCI data and the assessment of their quality and their appropriateness in relation to the goal of the study.

The life cycle inventory of primary aluminium (2010 update) is the result of a large task of collecting information from numerous production sites all over the world. The resulting inventories based on this huge task are acknowledged and appreciated.

2 Scope of the LCI and of the elementary flows

The life cycle inventory data comprise relevant information on energy, water and working materials consumption, air and water pollutant emissions, and wastes generated. A special emphasis is put on the water balance by reporting water abstraction and water discharge separately. This helps distinguishing between water withdrawal and water consumption and thus water use data are suitable for different water footprint assessment methods currently available. However, a regionalised assessment of water use is not yet possible because of lacking geographical information.

Particulate matter emissions are reported by specifying the share of particulates with diameters below 2.5 µm. This is of high value with regard to environmental impact assessment because smaller sized particular matter tends to cause more damage to human health than the same mass of larger sized particulate matter.

Special attention is given to the PFC emissions. The global average emission factors of CF_4 and C_2F_6 are based on a large sample of measurements. The specific emissions (per ton of primary aluminium) continued to decrease since the last update.

Land use impacts get more and more attention in the LCA community. Several impact assessment approaches covering either impacts on biodiversity or impacts on ecosystem services are now available. According to the outcome of an international workshop on life cycle impact assessment held recently in Glasgow (Jolliet & Frischknecht 2013), land use is considered to be one of the impact categories, which are relevant and bear the potential for global harmonisation. It is recommended to include land use information in the next data survey related to the value chain of primary aluminium, in particular related to bauxite mining and alumina production.

Bauxite residues (red mud) from alumina production are quantified as "solid waste". These residues are stored in large ponds or are stacked. Emissions from these so called bauxite residue storage areas (e.g. heavy metals in leachate) are not quantified. It is recommended to provide information about the environmental impacts of bauxite residue treatment with the next update.

3 Geographical and temporal scope

The survey coverage is reported individually for the different production processes and for each input and output. This information is very valuable and gives a detailed picture about the representativeness of the data. The survey coverage of bauxite mining, of energy in alumina and aluminium production and of anode effect is about 50 % (plus/minus 5 % points). It is lower for the LCI survey of alumina and aluminium production (38 % and 27 %, respectively). Not all responding sites report data on all transport services, energy, material and water inputs, pollutants emissions or wastes. In few cases of minor importance the coverage of reported figures is below 10 % of global production. Hence, the representativeness of the data is good regarding energy and PFC emissions and fair with regard to the remaining inputs and outputs. Chinese production is approximated with average global data represen¬ting the same technology. The global electricity mix used in primary aluminium smelters includes the Chinese production share and thus includes the Chinese electricity mix (mainly coal based) accordingly. It remains unclear whether these approximations are appro¬priate or lead to a significant bias in the final results as energy efficiencies and emission factors per ton of aluminium produced in China might differ substantially from the rest of the world average.

While the huge effort of data collection along the supply chain is acknowledged, it is recommended to include Chinese facilities in the next survey and to generally try to increase the response rate.

3 Data handling and processing

Data averaging is done in a professional, sophisticated and solid manner. The relevant production volumes are considered. Zero values and "not reported" values are distinguished. Zero values are included in the averaging where appropriate and missing values are excluded.

5 Data uncertainty and data errors

All data are provided with uncertainty information (standard deviation, minium and maximum values) based on data and theoretical considerations. This information is very helpful in assessing the reliability of the LCI data.

Random checks of data revealed only a few and minor errors or inconsistencies which were verified and corrected for the final version of the LCI report.

6 Overall assessment of primary Aluminium LCI data

The life cycle inventory data of global primary aluminium production in 2010 are consistent, transparent, and of high quality. It provides the LCA practitioner with reliable life cycle inventory data of global primary aluminium. The lack of information about the Chinese primary aluminium production is addressed as good as possible. The publication of unit process data allows for a consistent implementation of the data into LCA databases worldwide. The data are thus suitable for LCA studies compliant with ISO 14040 and ISO 14044 (ISO 2006a & b) and for implementation in LCI databases which are in line with the UNEP SETAC Global Guidance Principles for Life Cycle Assessment Databases (Sonnemann & Vigon 2011).

For future updates it is recommended to including Chinese production in the survey, extending the inventory to cover land use and transformation and heavy metals leaching from red mud dumps, and regionalising the water use data.

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