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Cradle to gate: life cycle impact of primary aluminium production

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Abstract

Purpose The International Aluminium Institute's (IAI) aim was to publish life cycle inventory (LCI) data for use by life cycle assessment (LCA) practitioners through professional databases. The need to provide robust data stems from the increasing application of LCA as a tool for making material and design choices and the importance for representative, up-to-date information to underpin such studies. In addition to this, the institute aimed to evaluate the significance of potential environmental impacts, based on the LCI results, against a defined set of impact categories which can be tracked over time.

Methods Key environmental data collected as part of the IAI's long-running industry surveys provided the foundation for the life cycle inventory. In order to evaluate the environmental impact, direct input and output data for primary aluminium production were supplemented with background data for indirect processes available in GaBi version 6 (PE International, 2013b). A cradle-to-gate model was constructed with two distinct datasets, global (GLO) and global minus China (rest of world (RoW)). A partial life cycle impact assessment (LCIA) was completed using the models, and the following six CML (2001–Nov 2010) midpoint environmental impact categories were reported: acidification potential, depletion of fossil energy resources, eutrophication potential, global warming potential, ozone depletion potential and photo-oxidant creation potential. Water scarcity footprint of primary aluminium (Buxmann et al. in this issue) was also included.

Results and discussion The results indicated that the largest greenhouse gas contributions were attributed to the alumina refining and electrolysis unit processes in both datasets, with electricity and thermal energy, being the major contributing factors to these higher values. The energy intensive nature of primary aluminium production means energy supply can significantly influence the overall environmental impact. Electricity production was found to contribute between 25 % and 80 % to all impact category indicator results, with higher values in the global dataset, a result of the inclusion of Chinese energy data and the increased share of coal-based electricity consumption that it represents.

Conclusions The global aluminium industry remains dedicated to transparent reporting of its environmental impacts and ensuring that up-to-date, representative LCI data is available. Development of suitable methodologies for new indicators will be required to ensure that the industry continues to report accurately all its relevant impacts. Additionally, with the increased importance of Chinese aluminium production, inclusion of foreground data from Chinese production would further enhance the dataset from which the global impacts of aluminium production are assessed from cradle to gate.

Keywords Aluminium · Electricity · Energy · Global warming potential · Greenhouse gas · Impact categories · LCA · LCI

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1 Introduction

The metals sector has been subject to increased environmental scrutiny in recent years driven, in part, by market and regulatory demands for the demonstration of improved environmental performance and resource efficiency of processes and products (PE International 2014). The International Aluminium Institute (IAI) is a global institute with a current membership that represents over 60 % of worldwide bauxite, alumina and primary aluminium production. The IAI has a 30-year history of collecting and publishing data on the environmental performance of the global aluminium industry (International Aluminium Institute (IAI) Anode Effect Survey Report 2014c; IAI Aluminium for Future Generations Sustainability Update 2011a).

Recognising the increasing application of life cycle assessment (LCA) as a tool for making policy decisions as well as material and design choices, and the need for robust and up-to-date information for such studies (Leroy 2009), the institute in 2000 and 2007 published life cycle inventory (LCI) data for the primary aluminium industry from the years 1998 and 2005. This represented the latest and most comprehensive cradle-to-gate dataset on the primary aluminium industry, but it was clear that such data was not always being used in the development of LCAs. In the third round of data collection and publication for 2010 data, it was decided that the institute would not only publish global LCI data (IAI Life Cycle Inventory 2013a) but would make a concerted effort to have this data made available in proprietary and professional databases being used by the majority of LCA practitioners (GaBi and EcoInvent). It was also decided that, for the first time, the institute would report midpoint impact category indicator results, through a life cycle impact assessment (LCIA) based on the 2010 LCI and background data available through the GaBi database.

LCIA is a tool to evaluate the potential environmental and human impacts of resource use and industrial process emissions, identified and quantified in the LCI (IAI 2014a). This paper presents the methodology used for the 2010 global LCI as well as the methodology, models and results for the LCIA for primary aluminium globally (GLO) and for the world excluding China (rest of world (RoW)). The decision behind the split between GLO and RoW will also be explored.

The definition of the system boundary is a key methodological decision for any LCA (PE International 2014). To assess the full life cycle impact for any product, a *cradle-to-grave* LCA is required and should include the upstream processes, downstream manufacturing, use stage, recycling and end-of-life processes. For the purposes of this LCIA, which focuses on primary aluminium production, only *cradle-to-gate* data are included, where the gate is defined as primary aluminium ingot leaving the aluminium production process. The contribution of 'cold metal'—scrap or remelt aluminium—in the ingot casting flow is also excluded from the LCI and LCIA. The scope of this study also excludes the impacts of semi-fabrication and fabrication processes, use stage or end of life operations, but it does include the environmental impacts of background processes, such as electricity and ancillary material production associated with the primary aluminium production process as shown in Fig. 1. The functional unit for this study is therefore 1 kg of primary aluminium ingot[1] at the factory gate, and thus, it should not be used for comparison with other materials or products but more to demonstrate the environmental impact of the primary aluminium production process. However, the LCI data can, and should, be used for developing full LCAs that can contain product comparisons.

2 Methodology

2.1 Data collection

The IAI has conducted annual surveys of industrial energy use since 1980 and other key environmental data such as perfluorocarbon emissions, fluoride emissions and bauxite residue volumes, since the late 1990s. Much of this data is published freely on the institute's website (www.world-aluminium.org/statistics/). In addition to these regular surveys, the IAI has collected data specific to the development of life cycle inventories for the years 2000, 2005 and 2010. The survey forms to collect industry data that form the basis for this study (included as Appendices for reference in the Electronic Supplementary Material) were sent to statistical correspondents (both within and outside of the IAI membership) in early 2011 with a request for data for the calendar year 2010. Data was collected on a facility level with the data categories included in the LCI survey designed specifically to ensure that all relevant data were collected to cover the scope of this inventory. The data categories have been selected based on their environmental relevance specific to primary aluminium production or as they are widely acknowledged as industry measurements to monitor and report against environmental issues. The data collection and processing were monitored by a dedicated life cycle data review group that reported to the IAI Environment and Energy Committee.

Once the data was received from reporting companies, it was assessed internally. Quality checks were conducted by comparing a facility's newly reported data to its previously reported values and the average values from the 2005 study for plants using similar technologies and processes. To ensure the integrity of the data, all values were checked individually

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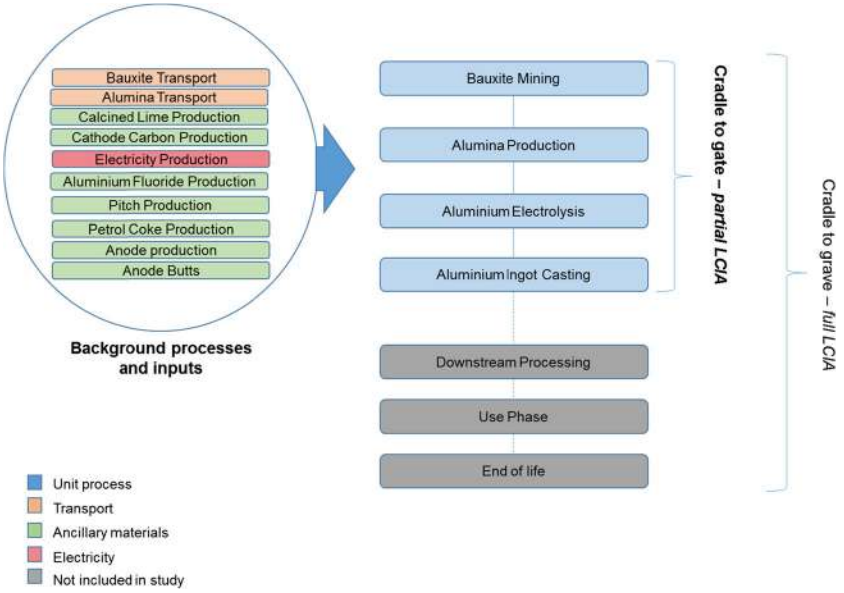
[1] Ingot specification of 98 % Al is used. Individual ingot specifications from reporters were not included in this study.

Fig. 1 System boundary of the cradle-to-gate study



and significant variations (±2 standard deviation) in reported data were queried with reporters and either confirmed or amended as appropriate. In addition, the data underwent third-party verification by an independent expert.

The collected data represented the direct inputs and outputs attributable to the processes at each facility. For indirect processes, such as production of ancillary materials, fuel and electricity, where specific data could not be supplied directly by the reporter, the background inventory datasets included within GaBi were used as a proxy. These background inventory datasets are sourced by GaBi from a number of reputable agencies such as European Aluminium, Plastics Europe and American Forest and Paper Association.

In the life cycle inventory, almost all averages were calculated as production-weighted mean values per tonne of relevant production output for those facilities that reported. There were some circumstances where this methodology did not accurately reflect specific process features, and so, alternative approaches were applied. Where there was an array of input/outputs per relevant process data (e.g. fuel mix), there was a need to count non-reported data points (zero values) so that a weighted average of a comprehensive array across the industry, and not just the average of a single criterion per production mass, was considered. This industrial weighted mean was used for seawater input, transport distances and fuel and power mix.

It should also be noted that as the ingot casting process excludes remelt or recycled aluminium, the LCI survey results for the ingot casting process yield a higher mass output than the electrolysis metal output. This was accounted for by adjusting the inputs and outputs from the survey average by a factor which was determined based on hot metal, alloying elements, total metal output and scrap sales. According to International Organization for Standardization (ISO) 14040 and 14044 (2006), this can be described as a situation of joint processes where a mass allocation approach is adopted. The absence of co-products for the unit processes considered in this study means that no other allocation methods were used.

Direct aluminium production process inventory data at the global level is published by the International Aluminium Institute per unit process (see Appendix I, Electronic Supplementary Material) and demonstrates, in part, the global aluminium industry's dedication to report openly its environmental impacts. The data collected serves as a credible basis for subsequent life cycle assessments of aluminium products. With the integrity of such datasets heavily dependent on the coverage and representativeness of the data received from the surveys, there are limitations with this approach that must be acknowledged. These are discussed in later sections.

2.2 Impact categories—selection, classification and characterisation

Six midpoint environmental impact categories for this study were selected in line with the recommendations from the harmonisation study for LCA methodologies across the metals industry (PE International 2014). In addition, the newly developed environmental indicator in the form of water scarcity footprint (Buxmann et al. in this issue; International Organization for Standardization (ISO) 14046 2014) was also considered. The impact categories selected are presented in Table 1, and they represent the most frequently used for life cycle impact assessment.

In addition to these categories, a breakdown of the relative contribution to global warming potential (GWP) of industrial processes in the primary aluminium value chain was included, along with a breakdown of total primary energy transformed. The exclusion of impacts for land use, abiotic depletion

Table 1 Pre-defined set of CML midpoint impact categories per kilogram of aluminium ingot

Category indicator results	Unit (per kg Al)	Methodology
Acidification potential (AP)	kg SO_2 e	CML 2001–Nov 2010
Depletion of fossil energy resources (depl. fossil energy)	MJ	Net cal. value
Eutrophication potential (EP)	kg PO_4 e	CML 2001–Nov 2010
Global warming potential (GWP 100 years)	kg CO_2 e	CML 2001–Nov 2010
Ozone depletion potential (ODP, steady state)	kg CCl_3F e	CML 2001–Nov 2010
Photo-oxidant creation potential (POCP)	kg C_2H_4 e	CML 2001–Nov 2010
Water scarcity footprint (WSFP)	m^3 H_2O e	ISO 14046 2014

potential (ADP), ecotoxicity and human toxicity are discussed in further detail in the Section 4.2 of this paper.

The Centre of Environmental Science (CML) methodology was selected to define the characterisation factors that convert the IAI inventory data to the common unit of the category indicator which allows determination of indicator results. This methodology is in line with the recommendations for LCIA methodologies in the metals industry and, in particular, for those with a global coverage (PE International 2014). The classification and characterisation of impact categories allow evaluation of their significance within the life cycle and over time. In this assessment, classification and characterisation were completed simultaneously. The classification process involves assigning inventory results to the impact categories listed in Table 1. Data used in the GaBi database for classification of the LCI results according to the impact categories is published by the following organisations: ISO, Society of Environmental Toxicology and Chemistry (SETAC), World Meteorological Organization (WMO) and Intergovernmental Panel on Climate Change (IPCC). The impact categories in Table 1 represent the accumulated impacts of the inputs and outputs of the system using category indicators. During the development of characterisation factors, consideration was given to a number of key influences including geography, population densities, chemistry, emission rates and other such technical characteristics that define the relationship between environmental flows and their potential impacts.

2.3 Data modelling

The modelling software used for this cradle-to-gate study was GaBi 6 (PE International 2013b). The GaBi model is built up through a hierarchical system which includes a series of plans and unit processes at its highest level. Figure 2 shows the plan for the IAI GaBi model for the GLO dataset and RoW dataset, within which the unit processes: bauxite mining, alumina production, electrolysis and ingot casting, are also visible. Each of these unit processes within the model is broken down into sub-systems which include a combination of direct industry data, i.e. IAI inventory, and background data for ancillary materials or processes, representing the inputs and outputs for each of the unit processes. These datasets are available in GaBi on a unit process level and can be interrogated down to the elementary flow level. The aluminium inventory data within GaBi has the added potential to be regionalised for LCAs due to the modelling of regional energy data. This is particularly important considering the significant impact of different energy mixes.

Background inventory data for the following supplementary processes were used in the model: limestone production, caustic soda production, aluminium fluoride production, petroleum coke production, pitch production, electricity generation and supply, fuel production and supply and transportation. The background data within GaBi is sourced primarily from industry and is therefore considered technologically representative (GaBi Modelling Principles 2013) and up-to-date. In addition, all data are compliant with the guidelines issued by the International Reference Life Cycle Data System (ILCD), which serves, in part, as a measure of quality for such datasets being used in life cycle work.

The decision to model two datasets, GLO and RoW, was based on the fact that China's primary aluminium production and demand have been essentially balanced for some time. Chinese imports of primary aluminium in 2010 were estimated at just over 0.2 mt, whilst exports were just under 0.2 mt (Antaike 2011). This is a comparatively low level of trade for a country where consumption in 2010 was close to 16 mt (IAI 2013b). The low level of external trade, generally poor data coverage and a significantly different power mix to the rest of the world means that modelling two datasets allows for distinct conclusions to be drawn about the environmental impacts for the globally traded aluminium market in 2010. The main differences between the datasets are from the energy mix and PFC emission data. These, in turn, are highly dependent on smelting technology and background electricity grid mixes. The availability of Chinese electricity consumption data, the most material influence on environmental impact, adds robustness to the Chinese data included as part of the GLO dataset. This is discussed further in the Section 4.2.

The energy intensive nature of the primary aluminium production process means that representative modelling of

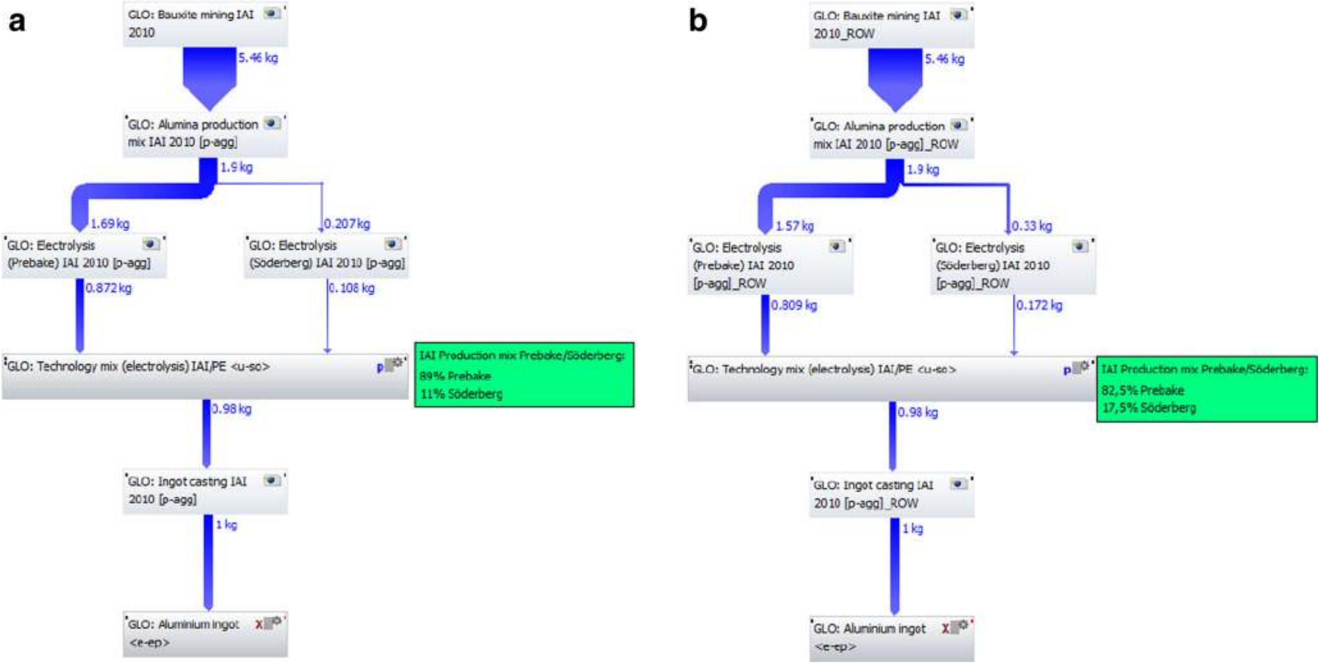


Fig. 2 **a** Global (GLO) data model plan in GaBi version 6 and **b** rest of world (RoW) data model plan in GaBi version 6

electricity supply systems and fuel mixes is critical to the accuracy and robustness of the output dataset. The electrolytic smelting process accounts for more than 95 % of total aluminium electricity consumption from cradle to gate, and the IAI has collected annual facility-level data on this input since 1980 (see Appendix II, Electronic Supplementary Material). The smelting electricity model developed in this study allows for the attribution of impacts, through the inclusion of background data, to regional industry-specific electricity mixes, rather than purely regional or national grid mixes, which for aluminium production is not always representative of the consumed power supply. This difference often stems from the aluminium smelter's requirement for abundant, competitively priced electricity to sustain operations. As such, producers are typically located in areas with access to low-cost, reliable electricity generation where long-term contracts are fixed. Increasingly, there has also been a move towards greater integration upstream, and now, some aluminium smelters have integrated power plants that feed their electricity requirements. In periods of surplus, electricity they generate can also be sold to the grid. It is this intimate link with energy supply that means the energy mix of a region can differ notably from that which serves its aluminium industry. In this paper, the industry-specific mixes used are GLO 2010 and RoW 2010, but the electricity model developed by the IAI has been included in GaBi 6, so that practitioners are able to build their own regional datasets, based on the IAI's regionalised power mix datasets (http://www.worldaluminium.org/statistics/primary-aluminium-smelting-power-consumption/) as seen in Tables 2 and 3.

The IAI's annual energy survey (Appendix II, Electronic Supplementary Material) of aluminium smelters provided energy carrier data for the regional datasets created in GaBi, each of which was supplemented by regional background data specific to the IAI regional power mixes. The datasets are aligned with the following IAI statistical regions: Africa, Asia, China, North America, South America, Europe and Oceania. These statistical regions are intended to maintain anonymity for individual companies reporting data to the IAI by aggregating data based on geographic spread. Proxy data was used for regions with limited background data; for example, South African energy carrier background data (but not electricity mix) was used for 'Africa'. The total impact of the electrolytic process and electricity consumption was calculated as the production-weighted average of impacts in all seven regions for GLO and six regions in the case of RoW.

The methodology adopted for thermal energy modelling was similar to that for electricity modelling. The impact of thermal energy input into the following unit processes was included: bauxite mining, alumina refining, anode production, paste production and ingot casting. A regional mix was constructed for each energy source, with the percentage share of each region again modelled (where necessary) on a relevant proxy background LCI dataset (e.g. Brazil for South America) present within the GaBi database. The global mix is a production-weighted average of the regional models, as for electricity.

In order to assess the contribution of the various processes to each impact category, the LCI data (IAI 2013a) is assigned

Table 2 Electricity sources by major region and for global and rest of world electrolysis datasets (any errors in total percentages are due to rounding)

2010	Africa	North America	South America	Asia (ex China)	Europe	Oceania	China	GLO (inc China)	RoW (ex China)
Reported Al production (000 tonnes)	1,441	4,440	2,210	1,855	7,981	1,542	16,194	35,664	19,469
Power mix (GWh)									
Hydro	9,181	50,355	29,145	4,817	97,271	5,211	22,638	218,618	195,980
Coal	11,844	16,095	0	8,171	13,856	17,932	203,745	271,643	67,898
Oil	0	7	0	138	238	6	0	389	389
Natural gas	0	316	5,591	15,510	5,015	0	0	26,432	26,432
Nuclear	0	320	0	0	10,677	0	0	10,997	10,997
Total	21,025	67,093	34,736	28,636	127,057	23,149	226,383	528,079	301,696

to specific typologies using the GaBi software. The four typologies to classify the processes and material inputs and outputs within the system boundary include

- **Direct and auxiliary processes**, encompassing material used in, or direct emissions associated with, the production of primary aluminium as well as the ancillary processes and materials such as caustic soda, lime and aluminium fluoride.
- **Transport** which includes the movement of input material via road, rail or ship.
- **Electricity** which includes the processes and materials needed to produce the electricity used directly in the production of aluminium.
- **Thermal energy** which includes the processes and materials needed to produce the thermal energy used directly in the production of aluminium but excluding the pitch and coke for anode production.

This methodology enabled the contribution of the relevant processes, to be displayed within the LCIA results in Section 3.

Water scarcity footprint (WSFP) for the production of primary aluminium was calculated using an approach in accordance with ISO 14046 (2014), and the concept is explored in significantly more depth by Buxmann et al. (in this issue). Essentially, the methodology for single site WSFP analysis incorporates direct water consumption from production sites along the aluminium value chain; indirect water consumption of the different ancillary materials, fuel and electricity needed for the production process; and a local water scarcity index (Pfister et al. 2009). A generic water scarcity footprint per tonne of primary aluminium was then determined by summing the direct and indirect WSFPs of the plants and normalizing it to the reference flow of 1 kg of primary aluminium.

Table 3 Electricity sources for global and rest of world electrolysis datasets (any errors in total percentages are due to rounding)

	GLO (GWh)	GLO %	RoW (GWh)	RoW %
Hydro	218,618	41 %	195,980	65 %
Coal	271,643	51 %	67,898	23 %
Oil	389	0 %	389	0 %
Natural gas	26,432	5 %	26,432	9 %
Nuclear	10,997	2 %	10,997	4 %
Total	528,079	100 %	301,696	100 %

3 Results

The impact category and additional indicator results (including GWP breakdown and primary energy) calculated using GaBi are reported in Table 4. In addition, the water scarcity footprint results, calculated separately in accordance with ISO 14046 (2014), are reported alongside.

As seen from the results in Tables 5 and 6, the largest greenhouse gas (GHG) contributions are attributed to the alumina refining and electrolysis unit processes in both datasets. Both the GLO and RoW datasets have similar contributions for bauxite mining, anode production and ingot casting. The difference noted for primary energy (MJ) is the result of including Chinese, coal-based production in the GLO dataset. The most significant differences within the alumina refining and electrolysis processes are the values for electricity and thermal energy. For example, GHG values for electricity in electrolysis are 9.2 kg CO_2-equiv./kg Al for the GLO dataset and 4.6 kg CO_2-equiv./kg Al for the RoW dataset. These differences stem from the coal-based energy production adopted in China, a country that accounted for 45 % of global aluminium production in 2010 (see Table 2) and over 50 % of global production currently. Coal-fired power plants account for 90 % of Chinese primary aluminium production compared to 70 % for the Chinese grid mix. Again, such disparities between regional energy mixes and energy mixes for the

Table 4 Global and RoW impact category indicator results (per kilogram of Al)

IAI impact category indicator results (per kilogram of primary ingot)	GLO 2010	RoW 2010
Acidification potential (AP) [kg SO_2-equiv.]	0.13	0.090
Depletion of fossil energy resources (depl. fossil energy) [MJ]	163	109
Eutrophication potential (EP) [kg phosphate-equiv.]	0.011	0.0053
Global warming potential (GWP 100 years) [kg CO_2-equiv.]	16.5	10.8
Ozone layer depletion potential (ODP) [kg R11-equiv.]	2.9E-10	2.8E-10
Photochemical ozone creation potential (POCP) [kg ethene-equiv.]	0.0085	0.0047
Water scarcity footprint (WSFP) [m^3 water-equiv.]	0.018	0.010

production of aluminium exist due to the intimate relationship that often exists between energy supply and smelting.

Full scenario modelling is beyond the scope of this study, but Table 7 shows some preliminary analyses looking at the environmental impacts if process technology for 2010 were 100 % prebake or 100 % Soderberg. The impacts for the GLO Soderberg database, when compared to the impacts for the GLO 2010 IAI base case (Table 4), are notably higher for all six impact categories considered. The results for the RoW Soderberg dataset shows that only three of the impact categories, global warming potential, eutrophication potential and depletion of fossil energy resources, are greater than the base case, with the other three impact categories, acidification potential, ozone layer depletion potential and photochemical ozone creation potential, all having slightly lower impacts. The impact category indicator results for GLO prebake and RoW prebake are more closely aligned with those presented for the base case owing to the greater proportion of prebake technology (89 %) for the 2010 base case.

4 Discussion

4.1 General

As is clear from the results of this study, the energy intensive nature of aluminium production means that energy supply plays a significant role in the overall environmental impact, with background processes accounting in some cases for the major proportion of impact. Figures 3 and 4 show that electricity production contributes between 25 % and 80 % to all impact category results, with higher values observed in the global dataset, a result of the inclusion of China and the increased share of coal-based electricity consumption that it represents.

Through comparison of the two datasets, it can be inferred that aluminium production in China, and more specifically electricity generation for aluminium production, contributes significantly to the impacts on a global basis. As noted in the IAI's Environmental Metrics Report Review (IAI 2014b), technology plays some part in reducing the environmental impact of the production process in China with the widespread use of prebake electrodes, which are less polluting than Soderberg electrodes. However, the country's heavy reliance on coal-powered electricity for the production of primary aluminium will continue to impact the environmental performance of the country's production.

As seen in the breakdown of GHG emissions in Tables 5 and 6, electricity production for electrolysis is the largest contributor to GWP, accounting for 56 % of the total for GLO and 43 % of the total for RoW. Thermal energy production for direct use in alumina refining contributed 13 % for GLO and 15 % for RoW.

Other significant influences on the GWP results are direct emissions from the electrolysis process which accounted for 14 % of the total for GLO and 20 % for RoW total. The emission of perfluorocarbon gases tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6) during anode events

Table 5 Global greenhouse gas emissions split by unit process and process type and primary energy input (renewable (R) and non-renewable energy (NR)) split by process type

GLO	Bauxite mining	Alumina refining	Anode/paste production	Electrolysis	Ingot casting	Total	Primary energy (MJ)	
							R	NR
Electricity	<0.1	0.4	<0.1	9.2	<0.1	9.7	27	104
Process and auxiliary	<0.1	0.7	0.4	2.3	<0.1	3.5	0	18
Thermal energy	<0.1	2.2	0.1	<0.1	0.1	2.4	0	31
Transport	0	0.5	<0.1	0.4	0	0.8	0	10
Total	<0.1	3.8	0.6	11.9	0.2	16.5	27	163

Table 6 RoW greenhouse gas emissions split by unit process and process type and primary energy input (renewable (R) and non-renewable energy (NR)) split by process type

RoW	Bauxite mining	Alumina refining	Anode/paste production	Electrolysis	Ingot casting	Total	Primary energy (MJ)	
							R	NR
Electricity	<0.1	0.1	<0.1	4.6	<0.1	4.8	42	55
Process and auxiliary	<0.1	0.7	0.4	2.2	<0.1	3.4	1	18
Thermal energy	<0.1	1.6	0.1	<0.1	0.1	1.8	0	26
Transport	0	0.5	<0.1	0.3	0	0.8	0	10
Total	<0.1	2.8	0.6	7.2	0.2	10.8	44	109

significantly impacts the GWP results due to the long atmospheric lifetimes associated with these potent greenhouse gases. Industry data on anode effects has been collected over the past 30 years and shows a significant decline in the intensity of perfluorocarbon emissions both on a total emissions basis and on an intensity basis. The IAI's LCI report (IAI 2013a) notes that CF_4 and C_2F_6 were reduced on an intensity basis by 34 % and 47 %, respectively, from 2005 levels. This is in line with the industry wide trend for lower global perfluorocarbon emissions from the aluminium industry between 1990 and 2010 (http://www.world-aluminium.org/statistics/perfluorocarbon-pfc-emissions/) through improved cell management and changing technology mix. It is estimated that between 1990 and 2010, a reduction in total emissions of over 70 % or over 90 % on an intensity basis (as CO_2-equiv.) has been achieved.

Looking at the effect of technology on the environmental impact indicator values, it can be seen that Soderberg technology has a greater impact across all six impact categories compared to prebake technology. Generally, Soderberg technology is older and less energy efficient (IAI 2013b), explaining the slightly higher environmental impact indicator values. As this technology is phased out in favour of newer prebaked carbon anode technology, some technology-related improvements can be expected to translate to the industry's impacts. It is worth noting however that the difference in impact category indicator values between the two technology types is not substantial and any technology-related improvements are likely to be marginal. It is in fact the energy source used for electricity generation which has the greatest influence on the environmental impact of the primary aluminium production process. The impact of different technology mixes on environmental indicator category values has begun to be explored in this study, and further scenario development should be considered as a separate study.

4.2 Limitations

The collection of data through the IAI surveys, although a major strength of this study (IAI 2014b), also gives rise to a number of potential limitations that must be addressed. Figures 5 and 6 show the reporting rates for the IAI surveys used in this study (IAI 2013a, 2011b, 2011c). Reporting rates for GLO 2010 are below 50 % for all categories except for LCI bauxite surveys and aluminium anode effect surveys. RoW reporting rates are notably better owing to the exclusion of China from this data. In the LCI database, assumptions are not made for non-reporting facilities, and so, Chinese industrial data is not represented in the inventory except for production data which is included in denominators for calculating reporting percentages.

The survey respondents for the 2010 LCI survey accounted for approximately 27 % of global primary aluminium production and 44 % of the RoW primary production (Fig. 5). Regions with good coverage (i.e. >60 % primary production) for the LCI include Western Europe, Middle East, North America and Oceania, the latter two with over 90 % coverage.

Table 7 Global and RoW impact category indicator results for 2010 with (a) 100 % Soderberg and (b) 100 % prebake technology (per kilogram of Al)

IAI impact category indicator results (per kilogram of primary ingot)	Soderberg		Prebake	
	GLO	RoW	GLO	RoW
Acidification potential (AP) [kg SO_2-equiv.]	0.14	0.09	0.13	0.09
Depletion of fossil energy resources (depl. fossil energy) [MJ]	179	116	161	108
Eutrophication potential (EP) [kg phosphate-equiv.]	0.011	0.005	0.011	0.005
Global warming potential (GWP 100 years) [kg CO_2-equiv.]	18.3	11.8	16.3	10.6
Ozone layer depletion potential (ODP) [kg R11-equiv.]	3.0E-10	2.9E-10	2.8E-10	2.8E-10
Photochemical ozone creation potential (POCP) [kg ethene-equiv.]	0.0088	0.0045	0.0085	0.0048

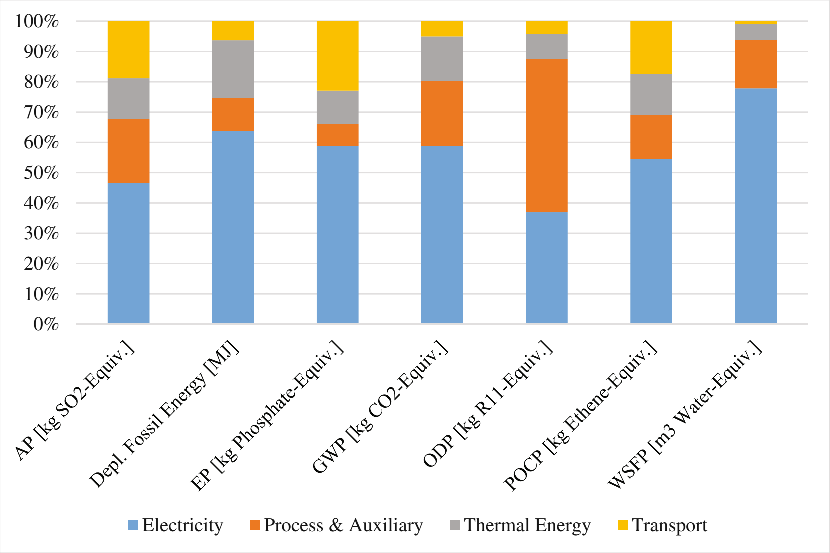


Fig. 3 GLO dataset, relative contributions to indicator results split by process type

Whilst it could be interpreted that the high reporting rates from facilities in these regions could impact representativeness of the dataset, it should be noted that the unit process data submitted by facilities included coverage across all existing major technology types. At the LCI level, the input and output data on the primary aluminium industry's processes tend to be a function of technology rather than regional location; therefore, the assumption that, on the whole, the non-reporting industry, a large proportion of which is China, would have technology performance equivalent to that of the reporting industry was considered a reasonable one. At the global LCA level, regional coverage can have a much greater impact. Background data, typically regionally (or in the case of power mix regional industry) aligned, comes into play, and in such instances, a high representation of a particular region in the background data would potentially influence the impact categories at a global level. The IAI has recognised the importance of power mixes that are specific to the regional aluminium industries and provides regular data on this (http://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/). Through our annual energy survey, approximately 47 % of the global industry reported energy data. In addition, Chinese aluminium industry energy data were reported to the IAI on an aggregated China-wide basis further adding to the representativeness of the IAI power mix data, the most significant influence on the industry's environmental impact.

Providing data by unit process with regional and industry specific energy mixes allows LCA practitioners to use the data for LCAs with greater levels of specificity than the global level that is presented in this study. Generally, reporting rates have consistently fallen over the past decade. The reasons for which are many and far-reaching, but we believe that the following have been key influences on declining reporting:

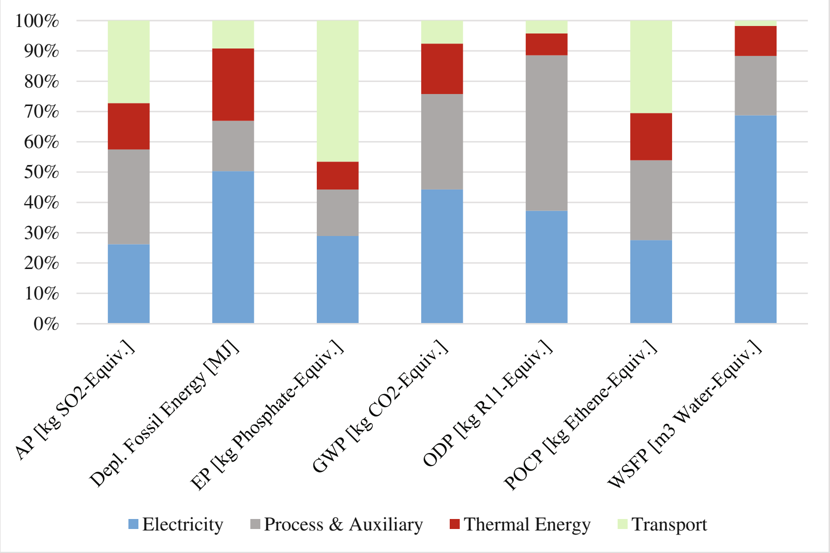


Fig 4 RoW dataset, relative contributions to indicator results split by process type

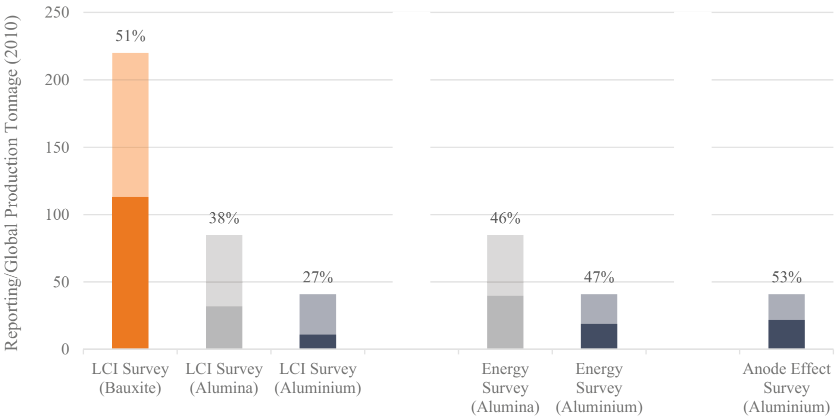


Fig. 5 GLO response rates and production figures for data year 2010. The *darker, shaded portions of each bar* represent respondents as a percent of global production (IAI 2013a, 2011b, 2011c)

structural change within the industry, i.e. mergers and demergers; the growing share of global production attributable to China, a region for which LCI survey response is notably low; and increasing reporting burdens on companies globally leading to more bureaucratic corporate reporting procedures. Reporting by Chinese producers is only captured by the annual energy surveys. As mentioned previously, whilst direct Chinese industry data is not included in these results, the use of robust background data on Chinese power mixes adds to the representativeness of the impact category indicator values because of its higher contribution to environmental impact than the proxy foreground data.

The modelling software itself also poses certain limitations with regards to the accuracy of the results, given that the quality of background datasets can vary considerably. Although the data within the GaBi database is ILCD compliant, some data can, under the ILCD guidelines, be up to 5 years old, and therefore potential for very new changes in technology or process to not be fully captured in the underlying numbers exists. However, energy data, the largest contributor to the impacts associated with primary aluminium production, is updated on an annual basis, and such lags that may exist with other background data for this study will likely have minimal effect on the output. A further consideration is the use of proxy datasets which will limit the level of accuracy that can be achieved. The effects of this have been reduced by the appropriate selection of the best available datasets, as advised by *PE International* who have extensive experience in such life cycle impact modelling.

The results of this study, together with the underlying data, provide an important platform from which LCA practitioners can draw upon when conducting global LCAs of products which contain aluminium. For LCAs where the origin of the primary aluminium is specified, data relevant to the specific regions, e. g. Europe or North America, should be used to provide a more representative assessment. Such data are not reported here but are typically available from regional associations such as European Aluminium (http://www.alueurope.eu/wp-content/uploads/2011/10/Environmental-Profile-Report-for-the-European-Aluminium-Industry-April-2013.pdf) or The Aluminium Association (http://www.aluminum.org/sites/default/files/LCA_Report_Aluminum_Association_12_13.pdf).

Although the most frequently used life cycle impact categories have been covered by this study, there are other important categories for aluminium production that have not been included. Notably, land use is not included as an impact category here due to its complexity and the limited availability of data from both the aluminium industry and background processes, which makes its quantification difficult and results highly uncertain. The exclusion of ADP as an impact category for this partial LCA is in line with the recommendations in the

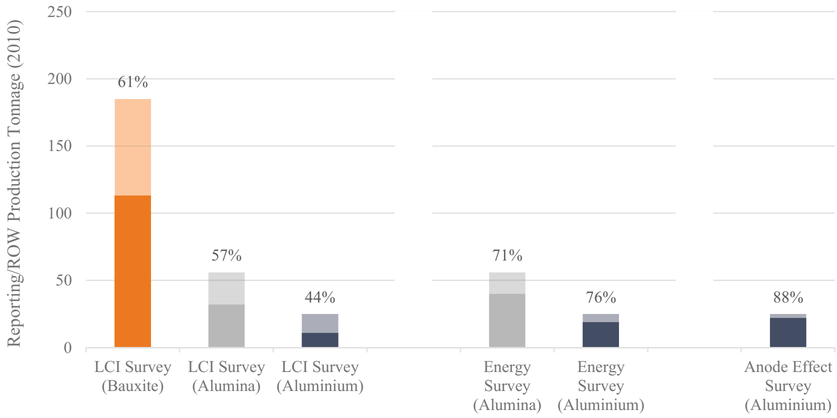


Fig. 6 RoW response rates and production figures for data year 2010. The *darker, shaded portions of each bar* represent respondents as a percentage of ROW production (IAI 2013a, 2011b, 2011c)

Harmonisation of LCA Methodologies for Metal Guidance (PE International 2014), where the two main approaches, total mineral content and economic feasibility, are considered contentious and based on assumptions that are not truly reflective of reality. Similarly, human toxicity and ecotoxicity, acknowledged environmental issues from the production of primary aluminium, are not included as impact categories here as the complex methodologies for their quantification, with respect to metal production, are not considered to be robust enough at present (PE International 2014). Ongoing research (Li et al. 2014; Kounina et al. 2014) supported by the aluminium industry through the IAI should ensure the inclusion of data and models for these important impact categories in future studies.

5 Conclusions and next steps

This cradle-to-gate LCIA study demonstrates the global aluminium industry's dedication to transparent reporting of its environmental impacts. The study also addresses the need for publication, and inclusion of robust, up-to-date and representative LCI data in databases for use by LCA practitioners in their studies. To ensure that the most relevant data is being used by practitioners, regular updates to datasets in software like GaBi and EcoInvent should be undertaken using data from the annual IAI energy use surveys and anode effect surveys. Additionally, the development of suitable methodologies to assess land use, ADP, human toxicity and ecotoxicity should be explored in greater detail. These categories are important for primary aluminium production, and the IAI continues to undertake research to address these issues. It is thought that with enhanced data collection, continued research and methodology testing on industry data, these important life cycle impact categories can be included in future studies. It would be beneficial for other major material producers to also develop methodologies to ensure that there is a degree of harmonisation in LCA studies and methodologies.

The LCI data collected by the IAI is on a 5-year cycle, and as such, a full update to the existing data will be conducted in 2016 using 2015 data. Both the impact and importance of Chinese aluminium production on global life cycle impact data need to be addressed. In subsequent studies, it is recommended that further detailed foreground data from Chinese production facilities be collated and included in the modelling. This should yield an improved global balance for aluminium production from cradle to gate and further enhance the accuracy of the data used for life cycle assessment.

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