International Aluminium Institute

LIFE CYCLE ASSESSMENT OF ALUMINIUM: INVENTORY DATA FOR THE PRIMARY ALUMINIUM INDUSTRY

YEAR 2005 UPDATE

SEPTEMBER 2007

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Executive Summary

The worldwide collection of aluminium data to be used in life cycle assessments was initiated by the 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."

In 2003 the International Aluminium Institute released its first Report ″Life Cycle Assessment of Aluminium: Inventory Data for the Worldwide Primary Aluminium Industry″ based on the year 2000. The present Report is an update for the year 2005. It has been prepared with the same view of collecting all significant Life Cycle Inventory data (raw materials and energy use, air and water emissions, solid waste generated) associated with producing *primary aluminium ingot* from bauxite ore, with worldwide coverage.

The 2005 Aluminium Life Cycle Inventory Data highlight the progress in environmental performance of the Worldwide Aluminium Industry, which increased its production output by 30% from 2000 to 2005. During the same period considerable improvements took place in production facilities, with phasing out of old plants notably some using Söderberg technology, and strong investments in new large-scale, up-to-date production capacities. Environmental improvements include the reduction of electricity consumption in electrolysis, PFC air emissions (-40%) and Spent Pot Lining (SPL) generation (-33%). The core plants included in the 2000 Life Cycled Inventory Data has since then been expanded. This explains the apparent deterioration in some results recorded in 2005.

1. Purpose of this inventory and relation to life cycle assessment

1.1. Goal and Scope Definition

The intended purpose of this Inventory Report is to accurately characterize resource consumption and significant environmental aspects associated with the worldwide production of primary aluminium. It reflects the fact that primary aluminium is a globally traded commodity.

The collected data will serve as a credible basis for subsequent life cycle assessments of aluminium products.

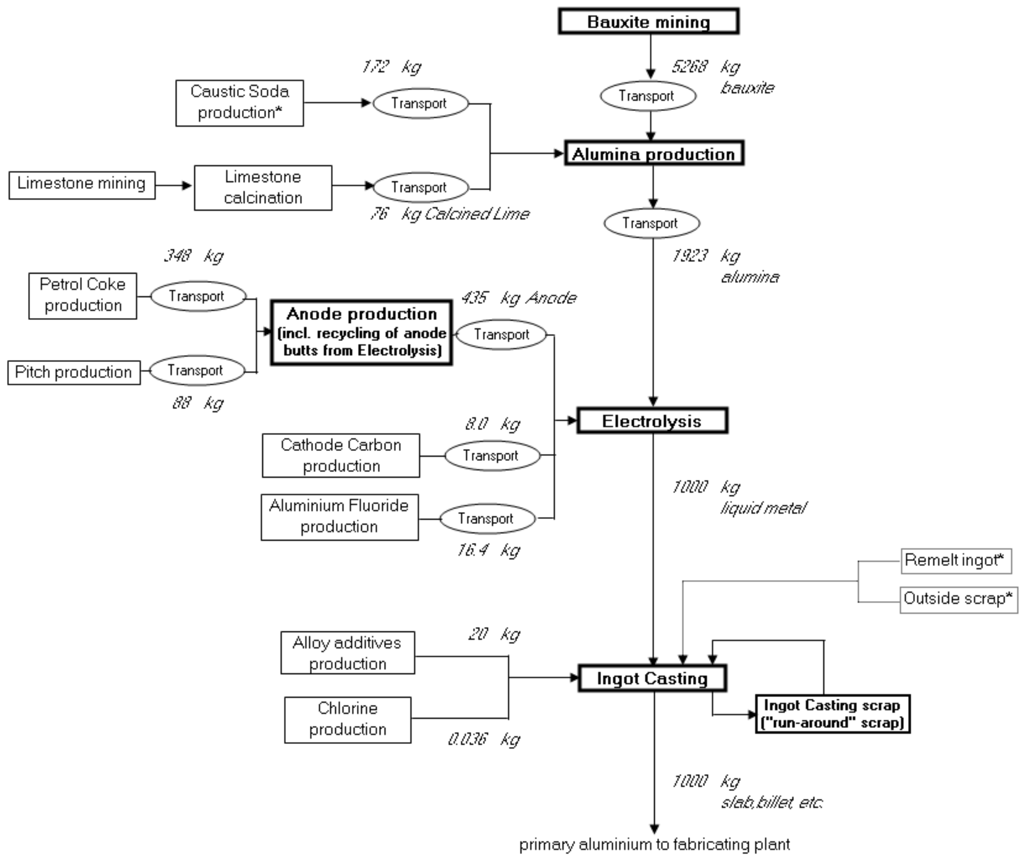
1.2. Process description and System Boundaries

The primary aluminium production covered by this Report includes the following unit processes:

- bauxite mining;
- alumina production;
- anode production: production of pre-baked anodes, production of Söderberg paste;
- electrolysis;
- ingot casting.

Unit Process descriptions are reported in Appendix A1.

The interrelationships of these unit processes are shown on the diagram below (in block characters and boxes), which provides an overview of material flows in the primary aluminium production. A short summary of this production is 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; next aluminium is cast into an ingot, the usual form suitable for further fabrication of semi-finished aluminium products. The diagram also shows other unit material processes not documented in the present work.



* contribution from remelt or recycled aluminium ("cold metal") is excluded as not representative for primary aluminium (see para. 1.4 reference flow)

No specific additional unit processes, in particular about energy production, transport, petrol coke and pitch production, caustic soda production, etc. have been added to the process in order to avoid non-elementary flows. LCA Practitioners who will use the data of this report may include such additional unit processes from their own databases **(*)**.

However special care is needed to include the appropriate electricity supply process, according to the reference information collected by IAI about energy source use. The global breakdown by source of electricity used at primary aluminium smelters in the IAI Energy Survey for 2005, was as follows: Hydro 57.3%; Coal 28.1%; Oil 0.7%; Natural Gas 8.8%; and Nuclear 5.1%.

Data related to the transport of materials were not covered in this Report. Environmental aspects from transport can be illustrated with a case from the “Environmental Profile Report for the European Aluminium Industry (April 2000)”, which yields the following air emission levels from transport in proportion of those generated from primary aluminium production: Particulates: 1.1%; HC: 29%; NO_x: 18.5%; SO_2: 6.7%.

1.3. Data collected

This Report contains only as-collected data, eventually combined together into an Inventory table for the worldwide Primary Aluminium Industry presented in section 3. Selection of data categories for this Inventory was based on their environmental relevance, either specific for the primary aluminium production (printed in block in the table below) or as generally acknowledged environmental issues. The data selection was confirmed in 2006 with a special meeting of the IAI Life Cycle & Sustainability Data Review Group. These data are listed below, with explanatory notes reported in Appendix A1.

It should be noted that only direct energy consumption figures were documented for this Inventory and that CO2 emission data were not included. Comprehensive energy data and CO2 emission data, including those associated with the generation of electricity, the production of fuel (pre-combustion) and the combustion of fuel, is monitored through special IAI Work Committees. A current summary of the CO2 emission data is reported in Appendix C.

(*) Note: a caution issue lies with air emissions from fuel combustion, namely Particulates, SO2 and NOx emissions. Reporting from plants in the present report included these emissions, together with process emissions, for improved reliability (see discussion about data interpretation in section 5) in particular as regards the effect of the actual sulphur content of fuel oil used on SO2 emissions. Accordingly LCA Practitioners who would include their own data sets about emissions from fuel combustion are recommended to remove their data about Particulates, SO2 and NOx emissions, in order to avoid double counting (note: this applies only to fuel combustion and not to “pre-combustion” data sets).

Inputs	Unit	Outputs	Unit
Raw materials			
		Air emissions	
Bauxite	kg		
Caustic Soda (for Alumina production)	kg	**Fluoride Gaseous (as F)**	kg
		Fluoride Particulate (as F)	kg
Calcined Lime (for Alumina production)	kg	Particulates	kg
		NOx (as NO2)	kg
		SO2	kg
Petrol Coke (for Anode production)	kg	Total PAH	kg
Pitch (for Anode production)	kg	BaP (Benzo-a-Pyrene)	g
		CF4	kg
Aluminium Fluoride (for Electrolysis)	kg	*C2F6*	kg
Cathode Carbon (for Electrolysis)	kg	HCl (Hydrogen Chloride)	kg
		Water emissions	
Alloy additives (for Ingot Casting)	kg		
Chlorine (for Ingot Casting)	kg	Fresh Water	m3
		Sea Water	m3
Other raw material inputs		**Fluoride (as F)**	kg
		Oil/Grease	kg
Fresh Water	m3	PAH (6 Borneff components)	g
Sea Water	m3	Suspended Solids	kg
Refractory materials	kg		
Steel (for anodes)	kg	**By-products for external recycling**	
Steel (for cathodes)	kg		
		Bauxite residue	kg
Fuels and electricity		*Dross*	kg
Coal	kg	Filter dust	kg
Diesel Oil	kg	Other By-products	kg
Heavy Oil	kg	Refractory material	kg
Natural Gas	m3	Scrap sold	kg
Electricity	kWh	*SPL carbon fuel/reuse*	kg
		SPL refr.bricks-reuse	kg
		Steel	kg
		Solid waste	
		Bauxite residue (red mud)	kg
		Carbon waste	kg
		Dross - landfill	kg
		Filter dust - landfill	kg
		Other landfill wastes	kg
		Refractory waste - landfill	kg
		Scrubber sludges	kg
		SPL - landfill	kg
		Waste alumina	kg

1.4. Reference flow

For each unit process the reference flow is 1 metric tonne. For the whole primary aluminium process as shown above and consolidated below in section 3, the reference flow is 1 metric tonne primary aluminium output from ingot casting.

Remark: for the unit process Ingot Casting, the reference flow has been specified excluding the contribution of remelt or recycled aluminium, which was considered outside the scope of the present work.

Namely, the overall average from the Survey results for the process Ingot Casting yielded a higher weight output (1000 kg) than the corresponding electrolysis metal input (955 kg), due to a "cold metal" input contribution from remelt aluminium (100 kg remelt ingot) and recycled aluminium (43 kg outside scrap). Because the scope of this Inventory report is primary aluminium and not remelt or recycled aluminium, data for the unit process Ingot Casting were calculated excluding the contribution from "cold metal", i.e. all inputs and outputs from the Survey average were adjusted by a factor of 0.88 (input ratio (electrolysis metal+ alloy additives = 974 kg) / (total metal input = 1117 kg) – see table 4a).

According to the ISO standards on LCA, this can be described as a situation of joint process where a mass allocation approach is applied.

1.5. Time Period Coverage

For this study, responses from worldwide aluminium producers were requested for the calendar year 2005.

1.6. Technology Coverage

The Aluminium Electrolysis data supplied came from all existing major technology types. About 22% of the total capacity surveyed was from Söderberg facilities and the remaining 78% was produced in Prebake facilities. Alumina production data supplied came from facilities currently in operation.

2. Data collection and Survey coverage

2.1. Organisation of data collection

Organisation of data collection was the same as for the previous year 2000 Inventory. Survey forms were sent out to statistical correspondents of all IAI Member Companies in February 2006 requesting data for the 2005 period. The values reported were assessed alongside previous reported values, standardised to per tonne of relevant product, to identify anomalous figures. Plants were queried on these figures, which were then confirmed or amended. This data collection and processing was monitored by a dedicated IAI Life Cycle &

Sustainability Data Review Group, itself reporting to the regular meetings of the IAI Environment & Energy Committee.

All statistics are quoted as 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). All data quoted are allocated to specific processes. Response rates express the number of plants that responded to an individual question in relation to the total number of plants answering the survey. In the final summary section 3, amalgamating inventory results across aluminium production processes, total is standardised to per tonne of aluminium.

Data reporting, trends and issues are further discussed in Appendix A3. Detailed results of the inventory analysis by process are reported in Appendix B.

2.2. Survey coverage

Data for the Life Cycle Survey were obtained from:

- 75 world-wide aluminium electrolysis plants producing 17.7 million metric tons of primary aluminium - a 20% increase compared to the 2000 Life Cycle production - representing about 55% of world-wide aluminium smelting operations.
- 10 world-wide bauxite mines producing 81.4 million metric tons of bauxite - which had not been documented with the 2000 Life Cycle - representing about 48% of world-wide aluminium bauxite mining operations.
- 24 world-wide alumina facilities producing 36.1 million metric tons of alumina - a 17% increase compared to the 2000 Life Cycle production - representing about 59% of world-wide alumina operations.
- 48 world-wide aluminium cast houses producing 12.2 million metric tons of primary aluminium ingot - 13% less compared to the 2000 Life Cycle production -, representing about 44% of world-wide aluminium ingot casting operations.

The survey response base was higher for the IAI Energy Survey and the IAI PFC Survey, which are established yearly IAI Surveys carried out separately as explained in Appendix A3. Overall, primary aluminium energy returns represented about 71% of world primary aluminium production; alumina energy returns represented about 73% of world alumina production; and PFC returns represented about 64% of world primary aluminium production.

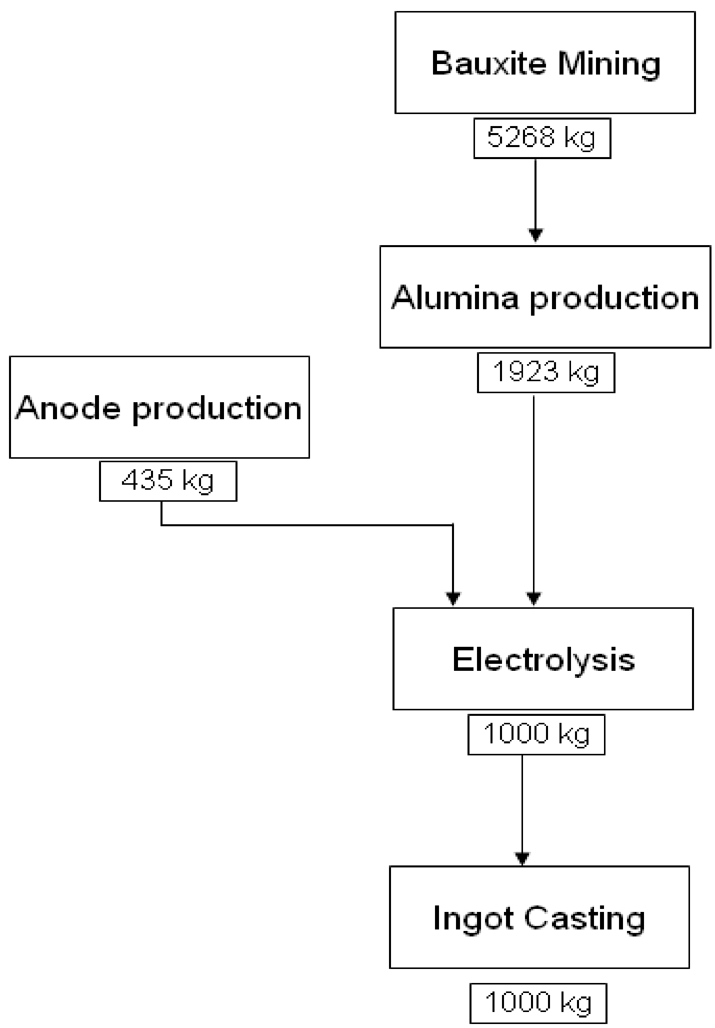
The increased coverage, as compared to the 2000 Life Cycle, means that new Member Companies provided answers to the Survey. Where comparability of results might be accordingly affected is discussed in Appendix A3.

Geographic coverage

The data were reasonably evenly distributed on a worldwide basis, the non-availability of data from China being mainly responsible for the comparatively poor coverage of Asia. For example, the survey's coverage of electrolysis plants in terms of reported primary aluminium production as a percentage of total primary aluminium production was about 85% in Africa, 87% in North America, 24% in Latin America, 14% in Asia (data for China not available), 78% in Europe and 100% in Oceania.

3. Inventory for the Worldwide Primary Aluminium Industry (year 2005).

The Inventory table for the Worldwide Primary Aluminium Industry reported below has been calculated from all results of inventory data. For this purpose the processes were combined together as shown in the following flow diagram.



Inputs

for 1000 kg Primary Aluminium

Process	Bauxite Mining	Alumina Production	Anode Production	Electrolysis	Casthouse	Total	Units
Raw materials							
Bauxite	5268					5268	kg
Caustic Soda		172				172	kg
Calcined Lime		76				76	kg
Alumina input						*1923*	*kg*
Petrol Coke			348				kg
Pitch			88				kg
Anode						*435*	*kg*
Aluminium fluoride				16,4		16,4	kg
Cathode carbon				8,0		8,0	kg
Aluminium (liquid metal)						*1000*	*kg*
Alloy additives					20	20	kg
Chlorine					0,036	0,036	kg
Cast ingot						*1000*	*kg*
Other raw material inputs							
Fresh Water input	2,6	15,2	<----	10,7	---->	28,6	m^3
indicative split			*1,0*	*5,3*	*4,5*		m^3
Sea Water input	0,3	0,2		17,6		18,0	m^3
Refractory material input (excluding SPL)			2,7	5,4		8,0	kg
Steel			2,2	6,6		8,9	kg
Fuels and electricity							
Coal		170	1,0		1,2	173	kg
Diesel Oil	6,0	1,3	1,0		1,4	9,7	kg
Heavy Oil	1,3	195	4,9		5,7	207	kg
Natural Gas	0,002	223	23		30	277	m^3
Electricity	10	242	56	15289	83	15680	kWh

Outputs

for 1000 kg Primary Aluminium

Process	Bauxite Mining	Alumina Production	Anode Production	Electrolysis	Casthouse	Total	Units
Air emissions							
Gaseous Fluoride (as F)			0,006	0,55		0,56	kg
Particulate Fluoride (as F)			0,001	0,49		0,49	kg
Particulates	5,0	0,33	0,09	3,7	0,04	9,2	kg
NOx (as NO2)		1,7	0,11	0,32	0,09	2,2	kg
SO_2		6,5	0,85	14,9	0,03	22,3	kg
Total PAH			0,028	0,29		0,32	kg
BaP (Benzo-a-Pyrene)			0,034	2,6		2,6	g
CF_4				0,13		0,13	kg
C_2F_6				0,013		0,013	kg
HCl (Hydrogen chloride)					0,009	0,009	kg
Mercury		0,40				0,40	g
Water emissions							
Fresh Water discharge	2,5	10,2	<----	10,2	---->	22,9	m^3
indicative split			*0,4*	*4,9*	*4,9*		m^3
Sea Water discharge	0,25	0,25		17,6		18,1	m^3
Fluorides (as F)			0,0002	0,32		0,32	kg
PAH (6 Borneff components)			0,055	1,64		1,69	g
Oil and grease/hydrocarbons		0,91	0,00004	0,008	0,009	0,92	kg
Suspended Solids		0,10	0,001	0,20	0,02	0,32	kg
By-products for external recycling							
Bauxite Residue		21,3				21,3	kg
Dross					11,7	11,7	kg
Filter dust					0,55	0,55	kg
Refractory material (excluding SPL)			2,9	2,3	0,2	5,4	kg
SPL - carbon				4,8		4,8	kg
SPL - refractory				4,0		4,0	kg
Steel			1,6	8,9		10,6	kg
Other by-products		10,7	2,7			13,4	kg
Solid waste							
Bauxite residue		2196				2196	kg
Alumina waste				2,6		2,6	kg
Carbon waste			7,9	6,9		14,8	kg
Dross - landfill					2,2	2,2	kg
Filter dust - landfill					0,14	0,14	kg
Refractory (excl. SPL) - landfill			0,8	0,5	1,0	2,3	kg
SPL - landfill				13,2		13,2	kg
Scrubber sludges			0,2	4,7		4,9	kg
Other landfilled waste		47,3	1,8		0,2	47	kg

Appendix A1: Unit Process descriptions and explanatory notes about Inventory inputs and outputs

The different Inventory inputs and outputs are reported in block italic letters within the following Unit Process descriptions for aluminium production.

1. BAUXITE MINING

Inventory analysis unit process description: Bauxite Mining
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 grading, dressing 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. Most all bauxite is mined in an open pit mine. The known reserves of alumina containing ore will sustain the present rate of mining for 300 to 400 years.

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

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

2. ALUMINA PRODUCTION

Inventory analysis unit process description: Alumina Production
This unit process begins with the 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 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*** (input taken conservatively whether the water used is from fresh, underground, mine waste water, etc. sources) 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 almost been halved over the last 15 years with the introduction of higher pressure digesters and fluid flash calciners.

<u>Air emissions</u> mostly arise from the calcination stage *(**Particulates; NOx (as NO2), SO2,*** from fuel combustion*; **Mercury*** found in ***Bauxite*** ores*),* while <u>Water emissions</u> come from cooling use (***Fresh Water, Sea Water, Oil/Grease***) or are linked with the digestion stage *(**Suspended Solids, Mercury*** found in ***Bauxite*** ores*).*

Most of the ***Bauxite residue*** currently turns out as <u>Solid waste</u>, while a small but growing fraction is reused. ***Other*** <u>by-products for external recycling</u> are reaction chemicals. ***Other Landfill Wastes*** are typically inert components from ***Bauxite*** such as sand, or waste chemicals.

3. ANODE PRODUCTION

Inventory analysis unit process description: Anode Production
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 output of this unit process is rodded anodes or briquettes transported to an Electrolysis plant (Primary Aluminium smelter).

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

Söderberg design uses a single anode, which covers most of the top surface of a reduction cell (pot). Anode paste (briquettes) is fed to the top of the anode and as the anode is consumed in the process, the paste feeds downward by gravity. Heat from the pot bakes the paste into a monolithic mass before it gets to the electrolytic bath interface.

The Prebake design uses prefired blocks of solid carbon suspended from ***Steel*** axial busbars. The busbars both hold the anodes in place and carry the current for electrolysis.

The process for making the aggregate for briquettes or prebake blocks 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 to atmosphere during the baking cycle to closed loop type designs that convert the caloric heat of the volatile into a process fuel that reduces energy consumption for the process. Baking furnace use ***Refractory materials*** for linings, ***Fresh Water*** (input taken conservatively whether the water used is from fresh, underground, mine waste water, etc. sources) as cooling agent. Baking furnace account for most of energy consumption (***Coal, Diesel Oil, Heavy Oil, Natural Gas, Electricity***).

<u>Air emissions</u>**:** ***Fluoride Gaseous (as F), Fluoride Particulate (as F)*** arise from recovered spent anode materials (un-used anode ends - “anode butts”) from Electrolysis (see below) recycled within Prebake Anode Production. ***Particulates, NOx (as NO2), SO2***, come typically from fuel combustion.
Total PAH, which includes ***BaP (Benzo-a-Pyrene)***, are air emissions generated from the basic Anode Production process.

The common practise for pollution control from Anode baking furnaces is scrubbing with alumina and returning the alumina to the electrolysis process. In 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 best practise and not the common method. The water emissions from paste and anode plants come from the cooling of the paste or green anodes.

By-products for external recycling: this means recovery of used ***Steel*** from anode bars, or of used ***Refractory material*** from baking furnaces. Various ***Other*** by-products are also recovered, e.g. carbon recovered for re-use.

Solid waste not recycled (landfill): ***Waste Carbon or mix*** is a residue from anode production, ***Scrubber sludges*** arise from water scrubbing used for control of air emissions mentioned above, ***Refractory*** waste comes out from baking furnaces Other landfill wastes arise as various residues, e.g. carbon fines.

4. ELECTROLYSIS

Inventory analysis unit process description: Electrolysis
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 hot metal transported to an ingot casting facility.

The Electrolysis process is also commonly named Aluminium Smelting.

Molten aluminium is produced from alumina (aluminium oxide) by the Hall-Heroult electrolytic process that dissolves the alumina in a molten cryolite bath (re: ***Aluminium Fluoride*** input) and passes current through this solution, thereby decomposing the alumina into aluminium and oxygen. Aluminium is tapped out of the reduction cell (pot) at daily intervals and the oxygen combines with the carbon of the anode to form carbon dioxide.

The pot consists of a ***Steel (for cathodes)*** shell lined with ***Refractory materials*** insulation and with a hearth of carbon (***Cathode Carbon (for Electrolysis)***). This is known as the cathode. 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

(***SPL carbon***) and a refractory-based part (***SPL refractory bricks***) are either recycled as by-products (***SPL carbon fuel/reuse, SPL refr.bricks-reuse***) or landfilled (***SPL – landfill***).

The current in a pot varies from 60,000 to over 300,000 amperes at a voltage drop of 4.2 to 5.0 volts. Pots produce about 16.2 plus/minus 0.6 pounds per day of aluminium for each kiloampere at an operating efficiency of 91% plus/minus 4%. ***Electricity*** consumption is the major energy aspect of Electrolysis.

Aluminium smelters typically use air pollution control system to reduce emissions. The primary system is typically a scrubber. Some plants use dry scrubbers with alumina as the absorbent 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 absorb emissions: the wet scrubbing process uses ***Fresh Water*** (input taken conservatively whether the water used is from fresh, underground, mine waste water, etc. sources) or ***Sea Water*** as input and result in corresponding ***Fresh Water*** or ***Sea Water*** discharges. Unlike dry scrubbers, wet scrubbers absorb 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.

Air emissions: specific aluminium Electrolysis process emissions are ***Fluoride Gaseous (as F), Fluoride Particulate (as F)***, which arise from the molten bath; ***Total PAH***, which includes ***BaP (Benzo-a-Pyrene)***, which arise from anode consumption; ***CF4*** and ***C2F6***, commonly reported as PFC, are gases generated with an uncontrolled anode overvoltage situation named “anode effect”. ***Particulates, NOx (as NO2), SO2***, come typically from fuel combustion.

Water emissions: ***Fluoride (as F)*** and ***PAH (6 Borneff components****: which are monitored because of their particular environmental effect****)*** arise from the same origin as their air emission equivalents above. ***Suspended Solids*** and ***Oil/Grease (***or ***total HC)*** are monitored in water discharges from wet scrubbing.

Solid waste: ***Other landfill wastes*** consist typically of about 60 % of "environmental abatement" waste (such as dry scrubber filter bags) and 40 % of "municipal" waste (source: North American Aluminum Association LCI report 1998).

5. INGOT CASTING

Inventory analysis unit process description: Ingot Casting
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 metal syphoned from the pots (***Electrolysis metal***) 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 fluxed to remove impurities and reduce gas content. The fluxing consists of slowly bubbling a combination of nitrogen and ***chlorine*** or carbon monoxide, argon and chlorine through the metal (***Chlorine*** use result in ***HCl (Hydrogen Chloride)*** air emissions). Fluxing may also be accomplished with an inline degassing technology, which performs the some function in a specialized degassing unit.

Fluxing removes entrained gases and inorganic particulates by floatation to the metal surface. These impurities (typically called ***dross***) are skimmed off. The skimming process also takes some aluminium and as such drosses are normally further processed to recover the aluminium content and to make products used in the abrasives and insulation industries.

Depending on the application, metal is then processed through an inline filter to remove any oxides that may have formed. Metal is then cast into ingots in a variety of methods: open molds (typically for ***remelt ingot***), through direct chill molds for various fabrication shapes, electromagnetic molds for some sheet ingots, and through continuous casters for aluminium coils. ***Fresh Water*** (input taken conservatively whether the water used is from fresh, underground, mine waste water, etc. sources) 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/Grease (***or ***total HC)*** are monitored.

Energy used for Ingot Casting is ***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 prefer to sell it out (***Scrap sold*** as <u>By-product for external recycling</u>). ***Dross***, ***Filter dust*** from melting furnace air filtration and ***Refractory*** material from furnace internal linings are either recovered as <u>By-products for external recycling</u>, or landfilled (***Dross – landfill***, ***Filter dust – landfill***, ***Refractory waste – landfill***).

<u>Solid waste</u>: ***Other landfill wastes*** consist typically of about 80 % of "environmental abatement" waste (such as metal filter box and baghouse) and 20 % of "municipal" waste (source: North American Aluminum Association LCI report 1998).

Particulates, SO_2, ***NO_x (as NO_2)*** <u>air emissions</u> are linked with fuel combustion.

Appendix A2: Overall mass balance in the aluminium production process

This section is to explain the main components of the mass distribution between 1000 kg aluminium output and other outputs from 5268 kg of bauxite input of the aluminium production process. This cannot be an exact calculation because reaction mechanisms are just outlined, due to uncertainty margins (inaccuracies) from the Survey results and also because the list of inputs and outputs is not complete due to data cut-off beyond the inputs and outputs selected for the inventory.

5268 kg of bauxite is the input for production of alumina (aluminium oxide). However there is always a significant water component in the bauxite, typically around 20 % (1054 kg). The non aluminium-containing part of the bauxite is disposed of as bauxite residue (red mud, 2196 kg) or recycled (21 kg). The mass balance out of the alumina production process would be around 2000 kg, after deduction of water component and bauxite residue.

Aluminium oxide (alumina) is converted in the electrolysis process (primary aluminium smelting) by the following reaction:

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

with a stoichiometric minimum requirement of 1890 kg Al_2O_3 for 1000 kg of primary aluminium.

The actual production process could be described as an alumina breakdown by electrolysis producing 1000 kg of aluminium and oxygen released on the carbon anode as CO_2 (where 435 kg coke and pitch input considered as carbon weight yield 1160 kg oxygen by difference with 1595 kg CO_2 corresponding output).

Appendix A3: Data reporting, trends and issues

Data collection took place through different surveys sent out to statistical correspondents of all IAI Member Companies, which together covered the entire scope of the Inventory:

- the 2005 Life Cycle Survey, where survey forms were designed in order to collect all required LCI data except those already collected through established yearly IAI Surveys, namely the IAI Energy Survey and the IAI PFC Survey.
- the 2005 Energy Survey collecting all energy data, and in addition some data which were earlier decided to be collected through the same Survey.
- the 2005 PFC Survey

As the Life Cycle Survey, the IAI Energy Survey and the IAI PFC Survey were carried out separately, they have not exactly the same survey response base. This is acknowledged in the inventory analysis tables in Appendix B, where results and survey base are differentiated between the Life Cycle Survey (normal characters) and the IAI Energy Survey or the IAI PFC Survey (italic letters).

Data reporting

Data reporting for the present Inventory of the world-wide Primary Aluminium Industry has been organised with quantitative and qualitative Data Quality Indicators (DQI), calculated for each data item:

<u>Quantitative Data Quality Indicators</u>: Precision (weighted mean values), Standard Deviation, Minimum and Maximum, Completeness.

- Precision: all values presented in the text of this report represent production weighted mean values for worldwide aluminium processes.

- Completeness: for each data item, this quality indicator covers the possibility where not all Survey respondents provided an answer. It is the ratio (number of responses for the data item) / (total number of responses to the Survey).

Data statistics assume a normal distribution of results. Examples of cumulative distribution graphs are reported in Appendix A4.

<u>Qualitative Data Quality Indicators</u>: DQI average and DQI range as representative indexes, calculated from the quality indicator provided by respondents for each individual answer among:

<u>1 (measured), 2 (calculated) and 3 (estimated)</u>

As these were not collected for 2005, values from the 2000 survey responses are reported.

Note: for data collected from the IAI Energy Survey and the IAI PFC Survey, those qualitative indicators were not collected, due to the different Survey procedure. However the DQI level can be considered as 1, in view of the thorough experience from these Surveys.

Data trends

As a general remark, it should be noted that the industry coverage has significantly improved from 2000 to 2005, often resulting in less visibility of Inventory Data improvements because of new respondents with lower environmental performance. Accordingly situations of apparent data stability always reflect in fact some underlying improvement. Closer consideration of each particular data item is needed in order to assess the actual improvement situation. This has been done in the following only for electrolysis electricity consumption.

<u>Raw materials</u>

Overall raw material use is about stable as compared to the 2000 Life Cycle Survey, except bauxite consumption which is up by about 2%, reflecting use of some lower grade ore.

<u>Electrolysis electricity consumption</u>

Electricity consumption in electrolysis is the major component of energy consumption in aluminium production. The 2005 figure (15680 kWh/t) is down 0.2% from the 2000 Life Cycle Survey (15711 kWh/t). This apparently modest reduction does not show a strong underlying improvement trend, due to contribution from new Survey respondents with comparatively lower performance. In fact considerable improvements took place in production facilities during the 2000 to 2005 period, with phasing out of old plants notably some using Söderberg technology, and strong investments in new large-scale, up-to-date production capacities.

A better assessment of this improvement trend can be derived from consideration of “core plants” only, i.e. those Member Companies having provided a response both in 2000 and in 2005 (representing about 80% of the primary aluminium production covered from the Survey). The 2005 figure (15056 kWh/t) is then down 1.2% from the 2000 Life Cycle Survey (15245 kWh/t), i.e. 0.25% reduction of electricity consumption per year. The actual 2000-2005 reduction in electricity consumption is however significantly higher as phasing out of old plants and investments in new ones is here far more influential.

Air emissions

Air emissions also are about stable as compared to the 2000 Life Cycle Survey, with however a strong improvement to be noted with ingot casting hydrogen chloride emissions down by more than 85 %. This improvement reflects replacement of chlorine by use of salt fluxing for melt purification, a change also visible from the reduction of chlorine consumption in ingot casting (-47%).

By-products for external recycling

Bauxite residue recycling shows a strong upward trend, although still small in quantities.

The percentage of SPL (Spent Pot Linings) recycled has somewhat decreased since the 2000 Life Cycle Survey, a trend in line with the overall reduction in SPL generation (see below).

Solid waste

Bauxite residue deposited is up about 15 % as compared to the 2000 Life Cycle Survey, a trend linked to use of lower grade bauxite ore in mining.

The total amount of SPL (Spent Pot Linings) generated in 2005, i.e. SPL recycled plus SPL land-filled, has decreased by 33% compared to the 2000 survey, a trend linked with phasing out of old smelters combined with improvements of existing operations. The amount spent pot linings going to landfills has reduced from 17.3 to 13.2 kg per tonne aluminium produced (-24%).

Dross from ingot casting operations sold as by-product is down 11%, whereas dross deposited is down 70%, a trend due to improved melt treatment and dross processing techniques.

Scrubber sludges from electrolysis are down by about 70 %, a trend due to increasing use of dry scrubbing for exhaust fume cleaning systems.

Data interpretation issues

Data weighting

Data are normally reported as production weighted mean values, i.e. derived from the effective responses to the Survey. In several situations mentioned below, however, this was not correctly reflecting specific process features, as reported below. Data reporting then took place as industry weighted use (reported as such in the Appendix B tables), i.e. the ratio “total consumption or emission reported from the Survey″ (total of all responses) to “total industry production” (total production of all respondents, whether or not responding on the particular data item):

- Petrol coke and pitch consumption for anodes (see table 3a), because weighted mean values from anode production tables are altered due to anode butt recycling.

- Sea Water use, either because used by a limited number of respondents for wet scrubbing - an alternate for Fresh Water scrubbing or for dry scrubbing (see Appendix A1, section 4 and note below) - or because of use (by only one respondent) as an alternate for Fresh Water.
  Note: Sea Water use is not normally involved with aluminium production. It is however used for smelter exhaust fume cleaning system, a process named wet scrubbing with seawater. This process is relevant to a limited number of companies, however involves accounting for significant quantities of input and discharged sea water, since the principle is based on diluting smelter air emissions into sea water to harmless concentrations.

- Fuel and electricity consumption for alumina and anode production, the rationale here being that the mix of fuel use is typically company-specific, i.e. using weighted mean values would lead to overestimated results.

Apparent inconsistency or weakness of evidence

Review of some results could raise remarks for apparent inconsistency or weakness of evidence. Noted examples are the steel input-output imbalance (likely to be attributed to a used steel output from general maintenance work) and the Ingot Casting mass balance (probably linked to the cold metal contribution). These cases can probably be considered as relatively non-significant, given the overall purpose of the present Inventory. It is also clear that the present Survey produced the best currently available knowledge for the worldwide Primary Aluminium Industry.

Air emission data from fuel combustion

Some air emission data from fuel combustion (an energy unit process not documented in the present work), namely Particulates, SO2 and NOx emissions, are included together with process emissions in the results reported from plants. This arises from the fact that the two emission types (from fuel combustion and from process) do occur together. This also corresponds to an improved reliability on actual emission levels from fuel combustion as compared to general fuel combustion emission data. In particular the actual sulphur content of fuel oil used, e.g. in alumina production, is thus most accurately accounted for in SO2 emissions.

Fresh water use

The use of Fresh Water for each sector is expressed in m3 per tonne produced.

Water is commonly used throughout the aluminium industry for cooling purposes. A typical use is cooling of metal (liquid or hot) after remelting. The cooling water is discharged after use, with constant monitoring of the quality of water effluents.

The water use for a given plant can be very different according to whether it is a single or multiple cooling use through water recycling systems – the latter resulting in a very low net water input. The system used depends on local water availability.

Issues with fresh water use measurement are reported below. Understanding these issues has significantly improved from 2000 to 2005 and will be further enhanced in future, with special emphasis on water-stressed areas.

Issues with Fresh Water use measurement

1) Differences in input and output (discharge) data from individual respondents originate from evaporation, rainwater and/or discharge within other output streams. Such situations have been queried and reasonably clarified, although the high variety of company water management systems prevent from a simple summary.

Some examples are as follows:

- Water evaporation from cooling uses should result with a water output lower than input.
- Rainwater included in discharge results in a water output higher than input, an effect visible in rainy areas.
- A significant case of discharge within other output streams occurs with alumina production when the water output is accounted for in red mud or other ancillary uses, leading to a zero water output.

2) Separate answers were asked from respondents about water use in Anode Production, Electrolysis and Ingot Casting. Often companies responded with figures for the entire plant only, i.e. for the 3 processes together. As a result this consolidated level for water figures was taken as most reliable, and the corresponding separate water data are for information only.

3) In the 2000 Survey, many apparent inconsistencies with Fresh Water use answers lead to outlier exclusion of responses, a procedure now discontinued, which eventually led to underestimated figures. Careful monitoring of individual situations, as explained above, has resulted in the resolution of this issue.

Mercury water emissions

Mercury water emissions from Alumina Production were not reported in the final inventory calculation due to lack of reliability (1 answer only).

Mining solid waste

Mining waste will have to be documented further in future Surveys, as presently there are too few answers, too extremely different from each other to allow understanding, making the weighted mean result quite unreliable. No data for mining waste have been reported in the final inventory calculation.

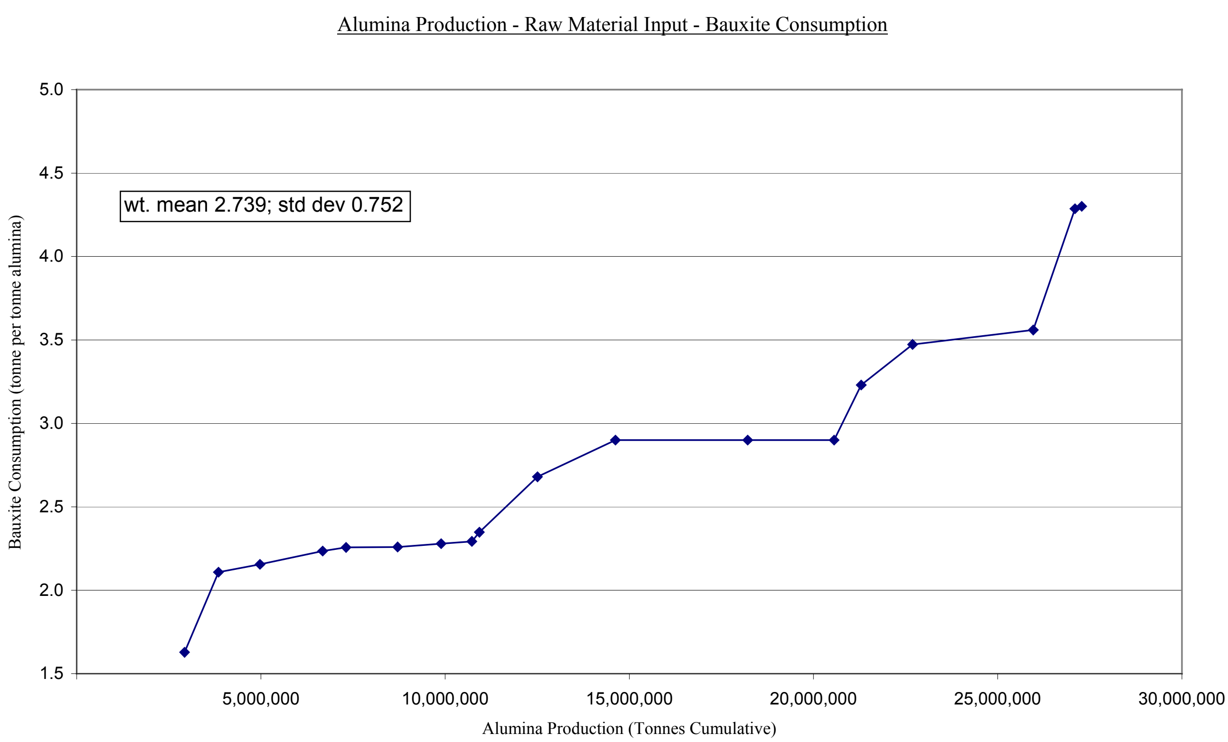
Dioxins emissions from Ingot Casting

Results for dioxins emissions from Ingot Casting have not been included in the final inventory calculation (1 answer only), as they are related to aluminium scrap remelting, which is outside the scope of this report (see reference flow section 1.4). Chlorine present in aluminium scrap (from painting or coating residues) is the origin element for dioxin emissions during aluminium remelting and there is no chlorine in primary aluminium.

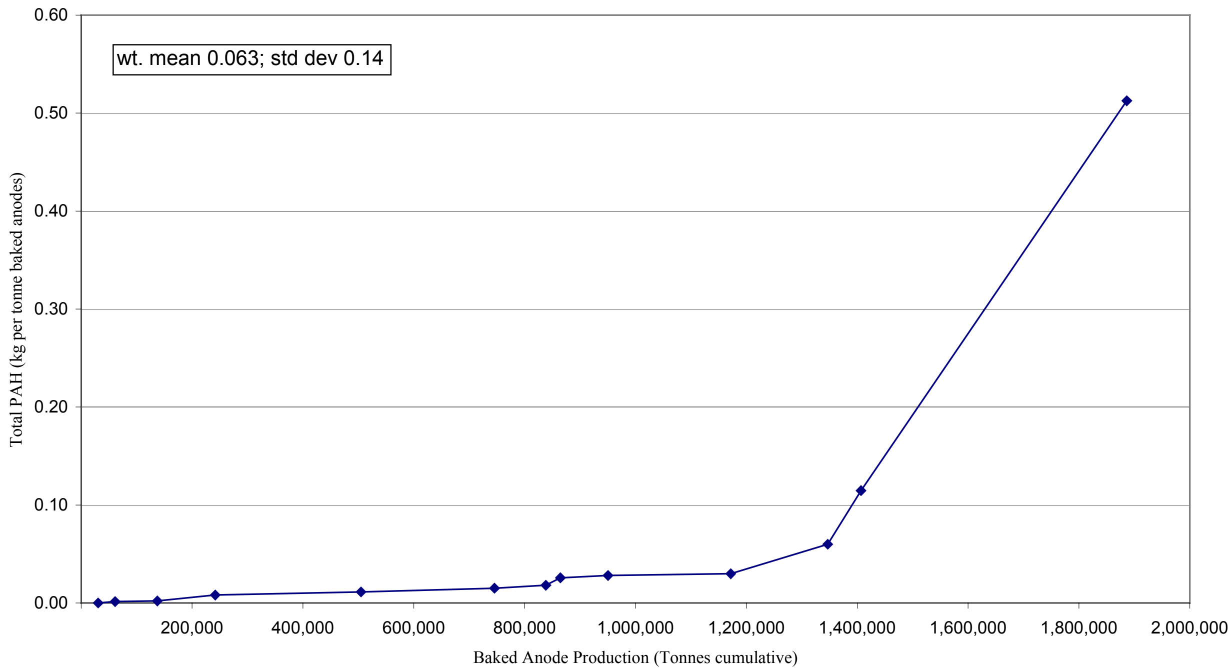
Appendix A4: Examples of cumulative distribution graphs

Data statistics assume a normal distribution of results. Examples of cumulative distribution graphs are reported below, in order to show typical actual data distribution:

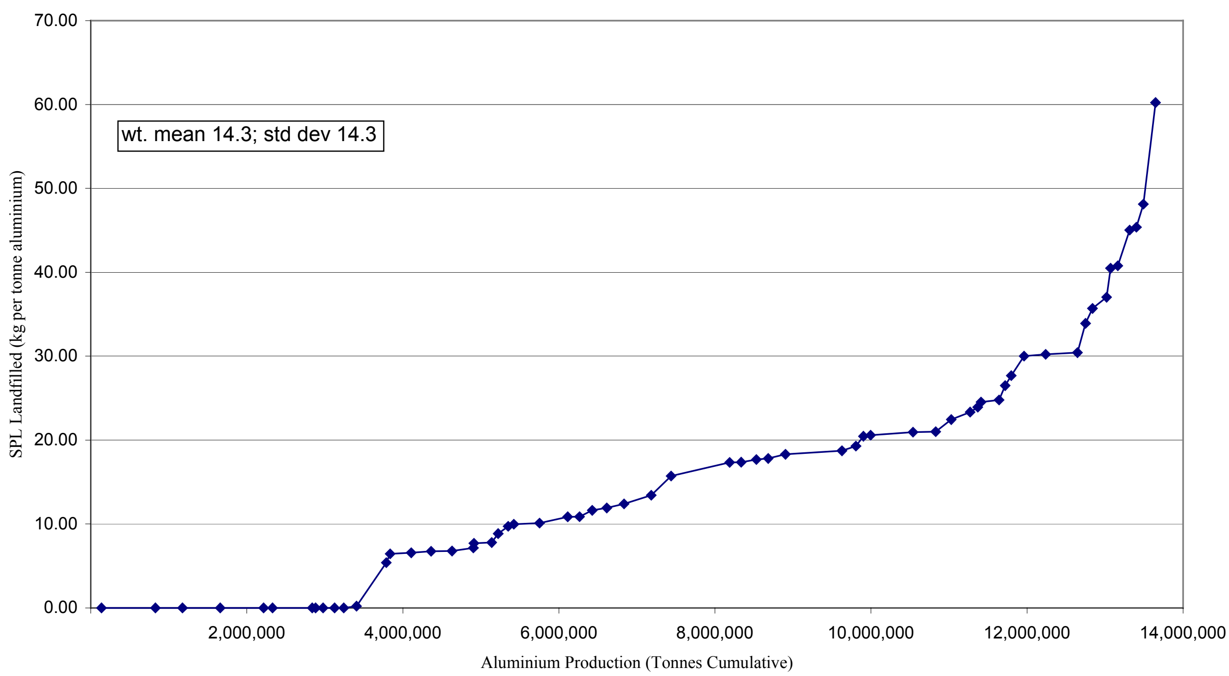
- Alumina production: Bauxite consumption (raw material input).
- Anode production: total PAH for Prebake anode production (air emission output).
- Electrolysis: SPL landfilled (solid waste not recycled output).
- Cast house: Fresh Water input.



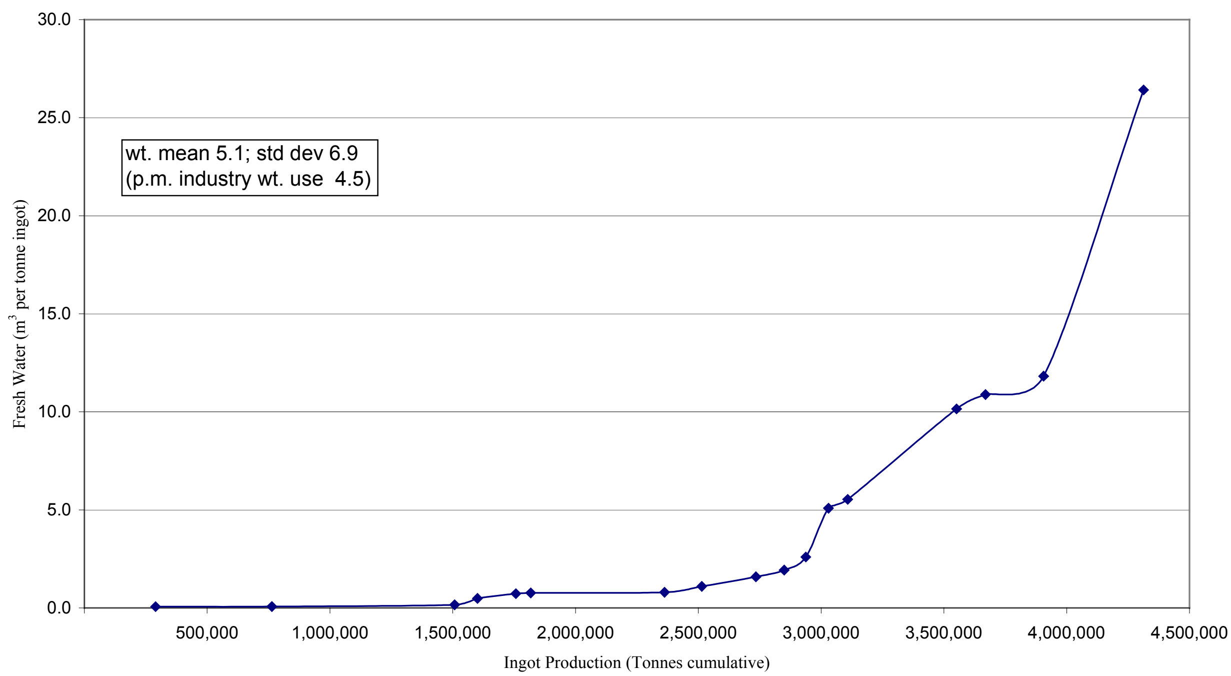
Baked Anode Production - Air Emission Output - Total PAH



Electrolysis - Solid Waste Not Recycled Output - SPL Landfilled



Ingot Casting - Fresh Water Input



Appendix B: Results of the inventory analysis by process

Results from the IAI Aluminium Life Cycle Survey 2005 are presented along the following Unit Processes, which have been consolidated together in section 3 to form the Inventory for the worldwide Primary Aluminium:

- Bauxite Mining
- Alumina Production
- Anode Production (Prebake)
- Paste Production (Söderberg)
- Reduction (Electrolysis)
- Ingot Casting.

Note: review of results displayed in the following tables should pay attention to data reporting either as production weighted mean values, which is the basic situation, or as industry weighted use, as discussed under “data interpretation issues”, Appendix A3. The applicable definitions are as follows:

- production weighted mean (“wt. mean"): total consumption or emission reported divided by total corresponding industry production of those plants which have reported data.
- industry weighted use (“industry wt. use”): total consumption or emission reported divided by total corresponding industry production.

Table 1s

IAI LCS 2005: bauxite mining

Life Cycle Survey

Total production:	**81363621 t**	Survey coverage of total world production:	**48%**
No. of mines:	10		

Inputs

Raw materials

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max
Fresh Water		0,50	1,2	m3/t	50	0,02	2,7
Sea Water	0,05	0,26	ns	m3/t	10	0,26	0,26

*per t bauxite

Fuels and electricity

	industry wt.use	wt. mean	std deviation	unit*	response rate(%)	min	max
Heavy Oil		0,25	0,4	kg/t	20	0,06	0,9
Diesel oil		1,1	2,0	kg/t	50	0,5	5,5
Gas		0,0003	ns	m3/t	10	0,03	0,03
Electricity		1,9	2,7	kWh/t	30	2,8	5,8

*per t bauxite

Outputs

Product: bauxite 1000 kg

Air emissions

	wt. mean	std deviation	unit*	response rate(%)	min	max
Particulates	0,95	5	kg/t	30	0,06	9,0

Water discharge

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max
Fresh Water		0,47	2,8	m3/t	60	0	7
Sea Water	0,05	0,26	ns	m3/t	10	0,26	0,26

Solid waste

	wt. mean	std deviation	unit*	response rate(%)	min	max
Mine solid waste	142	261	kg/t	30	0,3	452

*per t bauxite

Table 1

IAI LCS 2005: alumina production

Life Cycle Survey — **Total production: 36117800 t**; No. of refineries: 24 — Survey coverage of total world production: **59%**

IAI Energy Survey — *Total production: 45017011 t*; *No. of refineries: 35* — *Survey coverage of total world production: 73%*

Inputs

Raw materials

DQI = year 2000 data

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Bauxite		2739	752	kg/t	75	1628	4301	1,1	1-2
Caustic Soda		*90*	*30*	*kg/t*	*100*	*38*	*170*		
Calcined Lime		*39*	*21*	*kg/t*	*100*	*7*	*96*		
Fresh Water		7,9	29	m3/t	88	0,4	97	1,4	1-3
Sea Water	0,1	4,8	ns	m3/t	4	4,8	4,8	1,2	1-2

Fuels and electricity

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max
Heavy Oil	*101*	*154*	*122*	*kg/t*	*71*	*0,1*	*382*
Diesel oil	*0,7*	*1,6*	*2,2*	*kg/t*	*29*	*0,003*	*6*
Gas	*116*	*196*	*124*	*m3/t*	*46*	*0,4*	*388*
Coal	*89*	*333*	*207*	*kg/t*	*23*	*116*	*643*
Electricity	*126*	*164*	*118*	*kWh/t*	*80*	*1*	*428*

*per t alumina

Outputs

Product: alumina 1000 kg

Air emissions

DQI = year 2000 data

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Particulates	0,17	0,13	kg/t	38	0,01	0,5	1,6	1-3
SO2	3,4	4,5	kg/t	67	0,002	17	1,6	1-2
NOx (as NO2)	0,86	0,54	kg/t	67	0,3	2,1	1,8	1-3
Mercury	0,21	0,16	g/t	46	0,06	0,49	2,1	1-3

*per t alumina

Water emissions

DQI = year 2000 data

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Fresh Water		5,3	25	m3/t	88	0	92	1,9	1-3
Sea Water	0,1	5,5	ns	m3/t	4	5,5	5,5	1,3	1-2
Suspended Solids		0,050	0,2	kg/t	13	0,03	0,3	1,6	1-3
Oil and Grease/Total HC		0,47	0,72	kg/t	8	0,01	1,0	1,9	1-3
Mercury		0,00024	ns	g/t	4	0,00024	0,00024	1,9	1-3

*per t alumina

By-Products (for external recycling)

DQI = year 2000 data

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Bauxite Residue	11,1	51	kg/t	71	0	212	1,5	1-3
Other	5,6	14	kg/t	42	0,7	45	1,8	1-3

*per t alumina

Solid waste

DQI = year 2000 data

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Bauxite Residue (red mud)	1142	744	kg/t	83	460	3392	1,7	1-3
Other Landfill Wastes	24,6	28	kg/t	42	1,2	76	1,9	1-3

*per t alumina

Table 2a

IAI LCS 2005: anode production (combined Prebake-Söderberg)

Inputs

Life Cycle Survey	**Total production:**	**6524342 t**
	No. of anode/paste plants:	39
IAI Energy Survey	***Total production:***	***10030106 t***
	No. of anode/paste plants:	*78*

Raw materials

	wt. mean	unit*	response rate(%)
Petrol coke	*681*	*kg/t*	100
Pitch	*171*	*kg/t*	100
total	*852*	*kg/t*	

*per t anode

Note: recycled anode butts account for the raw material mass balance

Fuels and electricity

	industry wt. use	wt. mean	unit*	response rate(%)
Coal	*2,2*	*61,6*	*kg/t*	4
Heavy oil	*11,2*	*65*	*kg/t*	21
Diesel oil	*2,2*	*20*	*kg/t*	10
Gas	*54*	*77*	*m3/t*	65
Electricity	*129*	*173*	*kWh/t*	76

Other inputs

	industry wt. use	wt. mean	unit*	response rate(%)
Fresh water (wt.mean indicative only)	0,8	2,3	m3/t	33
Refractory material		6,1	kg/t	24
Steel		5,1	kg/t	8

*per t anode

Table 2a (P)

IAI LCS 2005: anode production (Prebake)

30-Aug-02

Inputs

Life Cycle Survey	Total production (baked):	4694193	t
	No. of anode plants:	27	
IAI Energy Survey	*Total production (baked):*	*8788998*	*t*
	No. of anode plants:	*59*	

Raw materials	wt. mean	std deviation	unit*	response rate(%)	min	max
Petrol coke	678	49	kg/t	100	588	795
Pitch	154	13	kg/t	100	129	187
total	832		kg/t			

*per t anode

Note: recycled anode butts account for the raw material mass balance

Fuels and electricity	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max
Coal	2,0	60	68	kg/t	3	14,2	110
Heavy oil	12,6	71	12	kg/t	19	51	94
Diesel oil	2,4	21	36	kg/t	10	0,15	90
Gas	61	80	31	m3/t	76	0,05	141
Electricity	141	182	115	kWh/t	80	0,02	479

*per t anode

DQI = year 2000 data

Other inputs	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Fresh water (wt.mean indicative only)	2,2	6,1	m3/t	33	0,14	15	1,8	1-3
Refractory material	8,5	7	kg/t	33	3,4	24	1,9	1-3
Steel	7,2	2,2	kg/t	11	4	8	1,9	1-3

*per t anode

Table 2a (S)

IAI LCS 2005: paste production (Söderberg)

30-Aug-02

Inputs

Life Cycle Survey	Total production:	1830149	t
	No. of paste plants:	12	
IAI Energy Survey	*Total production:*	*1241108*	*t*
	No. of paste plants:	*19*	

Raw materials	wt. mean	std deviation	unit*	response rate(%)	min	max
Petrol coke	699	27	kg/t	100	631	734
Pitch	296	28	kg/t	100	250	348
total	995		kg/t			

*per t anode

Fuels and electricity	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max
Coal	3,5	70	NA	kg/t	5	70	70
Heavy oil	0,93	7,3	5	kg/t	26	1,1	15
Diesel oil	0,95	10,9	9	kg/t	11	1,6	14
Gas	5,7	17,7	12	m3/t	32	7,4	33
Electricity	42	81	55	kWh/t	63	0,01	207

*per t anode

DQI = year 2000 data

Other inputs	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Fresh water (wt.mean indicative only)	9,0	22	m3/t	33	0,4	46	2,1	1-3

*per t anode

Table 2b

IAI LCS 2005: anode production (combined Prebake-Söderberg)

Outputs

Life Cycle Survey	Total production:	6524342	t
	No. of anode/paste plants:	39	

Product: anodes 1000 kg

By-products for external recycling

	wt. mean	unit*	response rate(%)
Refractory	6,6	kg/t	35
Steel	3,7	kg/t	8
Other	6,2	kg/t	5

*per t anode

Solid waste not recycled	wt. mean	unit*	response rate(%)
Waste carbon or mix	18,1	kg/t	39
Scrubber sludges	0,5	kg/t	24
Refractory (excl.SPL)	1,8	kg/t	35
Other landfilled waste	4,1	kg/t	11

*per t anode

Table 2b (P)

IAI LCS 2005: anode production (Prebake)

30-Aug-02

Outputs

Life Cycle Survey	Total production (baked):	4694193	t
	No. of anode plants:	27	

Product: Baked Anodes 1000 kg

By-products for external recycling DQI = year 2000 data

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Refractory	9,1	6,0	kg/t	48	1,7	21,6	1,4	1-3
Steel	5,2	5,5	kg/t	11	2,4	12,8	1,8	1-3
Other	8,6	9,6	kg/t	7	0,3	13,9	1,6	1-3

*per t anode

DQI = year 2000 data

Solid waste not recycled	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Waste carbon or mix	23,3	19,3	kg/t	41	0,9	65	1,5	1-3
Scrubber sludges	0,7	5,9	kg/t	33	0	18,2	1,4	1-3
Refractory (excl.SPL)	2,5	7,6	kg/t	48	0	23,9	1,9	1-3
Other landfilled waste	5,7	7,0	kg/t	15	0	14,8	1,6	1-3

*per t anode

Table 2b (S)

IAI LCS 2005: paste production (Söderberg)

30-Aug-02

Outputs

Life Cycle Survey	Total production:	1830149	t
	No. of paste plants:	12	

Product: anode paste 1000 kg

By-products for external recycling

	wt. mean	std deviation	unit*	response rate(%)	min	max
Refractory			kg/t			
Steel			kg/t			
Other			kg/t			

*per t anode

DQI = year 2000 data

Solid waste not recycled	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Waste carbon or mix	4,7	7,5	kg/t	33	0,10	15,2	1,7	1-3
Scrubber sludges			kg/t					
Refractory (excl.SPL)			kg/t					
Other landfilled waste			kg/t					

*per t anode

Table 2c

IAI LCS 2005: anode production (combined Prebake-Söderberg)

Outputs Air emissions

Life Cycle Survey Total production: 6524342 t
No. of anode/paste plants: 39

Air emissions	wt. mean	unit*	response rate(%)
Particulates	0,21	kg/t	67
SO2	2,0	kg/t	38
NOx (as NO2)	0,26	kg/t	28
Particulate Fluoride (as F)	0,0024	kg/t	35
Gaseous Fluoride (as F)	0,015	kg/t	32
Total PAH	0,064	kg/t	51
B(a)P	0,078	g/t	33

*per t anode

Table 2c (P)

IAI LCS 2005: anode production (Prebake)

Outputs Air emissions

Life Cycle Survey Total production (baked): 4694193 t
No. of anode plants: 27

DQI = year 2000 data

Air emissions	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Particulates	0,15	0,44	kg/t	70	0,006	1,6	1,4	1-3
SO2	1,8	3,1	kg/t	37	0,05	9,3	1,6	1-3
NOx (as NO2)	0,29	0,30	kg/t	26	0,14	0,96	1,7	1-3
Particulate Fluoride (as F)	0,0034	0,014	kg/t	48	0,00001	0,050	1,4	1-3
Gaseous Fluoride (as F)	0,020	0,17	kg/t	44	0,00019	0,61	1,2	1-3
Total PAH	0,063	0,14	kg/t	48	0,00001	0,51	1,5	1-3
B(a)P	0,083	0,57	g/t	33	0	1,7	1,7	1-3

*per t anode

Table 2c (S)

IAI LCS 2005: paste production (Söderberg)

30-Aug-02

Outputs Air emissions

Life Cycle Survey Total production: 1830149 t
No. of paste plants: 12

DQI = year 2000 data

Air emissions	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Particulates	0,39	0,57	kg/t	58	0,012	1,4	1,3	1-3
SO2	2,3	5,6	kg/t	42	0	12,3	1,6	1-2
NOx (as NO2)	0,17	0,43	kg/t	33	0,002	0,88	2,4	2-3
Particulate Fluoride (as F)			kg/t					
Gaseous Fluoride (as F)			kg/t					
Total PAH	0,066	0,071	kg/t	58	0,0001	0,19	1,1	1-2
B(a)P	0,063	0,097	g/t	33	0	0,19	1,6	1-3

*per t anode

Table 3a

IAI LCS 2005: electrolysis

Inputs

Life Cycle Survey	**Total production:**	**17659979**	**t**	Survey coverage of total world production:	55%
	No. of smelters:	75			
	of which Söderberg:	**3961771**	**t**		
	No. of smelters:	13	(No. of PB smelters: 67)		
IAI Energy Survey	***Total production:***	***22631991***	***t***	*Survey coverage of total world production:*	71%
	No. of smelters:	*113*			

Raw materials

DQI = year 2000 data

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
alumina (dry)		1923	39	kg/t	67	1825	2098	1,3	1-3
anode PB (net)		*425*	*23*	*kg/t*	*61*	*385*	*518*		
Söderberg paste		*514*	*31*	*kg/t*	*18*	*476*	*585*		
anodes (net)/Söd. paste	*435*			*kg/t*	95				
petrol coke	*348*			*kg/t*					
pitch	*88*			*kg/t*					

*per t aluminium (liquid metal)

Electricity consumption

	wt. mean	std deviation	unit*	response rate(%)	min	max
Electricity	*15289*	*1330*	*kWh/t*	*100*	*13513*	*19311*

*per t aluminium (liquid metal)

Other inputs

DQI = year 2000 data

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Fresh Water (incl. Anode Prod. & Ingot Casting >)		10,7	19	m3/t	89	0	90	1,6	1-3
Sea Water	17,6	165	116	m3/t	13	2	427	1,3	1-3
Cathode carbon		8,0	4,2	kg/t	45	0,4	20	1,6	1-3
Refractory material		5,4	5,9	kg/t	19	0,2	19	1,8	1-3
Steel		6,6	25	kg/t	29	0	121	1,8	1-3
AlF3		16,4	7,1	kg/t	89	0	35	1,1	1-2

*per t aluminium (liquid metal)

Table 3b

IAI LCS 2005: electrolysis

Outputs

Life Cycle Survey			
Total production:	17659979	t	Survey coverage of total world production: 55%
No. of smelters:	75		
of which Söderberg:	3961771	t	
No. of smelters:	13	(No. of PB smelters: 67)	

Product: liquid aluminium 1000 kg

Water Discharges — DQI = year 2000 data

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Fresh Water (incl. Anode Prod. & Ingot Casting >)		10,2	20	m3/t	65	0	72	1,7	1-3
Sea Water	17,6	152	121	m3/t	15	2	427	1,4	1-3
Suspended solids		0,20	1,1	kg/t	48	0,002	6,4	1,4	1-3
Oil & grease/total HC		0,0030	0,0102	kg/t	24	0,0001	0,041	1,6	1-3
Fluorides (as F)		0,32	1,2	kg/t	48	0,0006	7,0	1,4	1-3
PAH (6 Borneff components)		1,6	7,2	g/t	16	0,000003	25	1,5	1-3

*per t aluminium (liquid metal)

By-products for external recycling — DQI = year 2000 data

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
SPL carbon (wt.mean indicative only)	4,8	7	kg/t	35	0	14	1,2	1-3
SPL refractory (wt.mean indicative only)	4,0	9	kg/t	35	0	21	1,2	1-3
Refractory (other)	2,3	4,7	kg/t	31	0	20	1,3	1-3
Steel	8,9	7,6	kg/t	35	0	35	1,6	1-3
Other			kg/t				1,5	1-3

Solid waste not recycled — DQI = year 2000 data

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
SPL	13,2	13	kg/t	80	0	60	1,4	1-3
Waste alumina	2,6	10	kg/t	28	0	42	1,5	1-3
Waste carbon or mix	6,9	8,9	kg/t	36	0	31	1,4	1-3
Scrubber sludges	4,7	31	kg/t	17	0	104	1,3	1-3
Refractory (excl.SPL)	0,5	0,6	kg/t	31	0	2,5	1,6	1-3
Other landfilled waste			kg/t				1,6	1-3

*per t aluminium (liquid metal)

Table 3c

IAI LCS 2005: electrolysis

Outputs **Air emissions**

Life Cycle Survey	**Total production:**	**17659979 t**	Survey coverage of total world production:
	No. of smelters:	75	**55%**
	of which Söderberg:	**3961771 t**	
	No. of smelters: 13	(No. of PB smelters: 67)	
IAI PFC Survey	***Total production:***	***20160509 t***	*Survey coverage of total world production:*
	No. of smelters:	*111*	***63%***

Air emissions

DQI = year 2000 data

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Particulates	3,7	9,0	kg/t	60	0,5	38	1,3	1-3
SO2	14,9	7,6	kg/t	92	0,3	33	1,7	1-3
NOx (as NO2)	0,32	0,4	kg/t	72	0,0003	1,8	1,8	1-3
Particulate Fluoride (as F)	0,49	1,2	kg/t	81	0,06	7,8	1,3	1-3
Gaseous Fluoride (as F)	0,55	0,8	kg/t	85	0,002	4,0	1,2	1-3
Total PAH	0,29	0,66	kg/t	20	0,0006	2,5	1,8	1-3
B(a)P	2,6	4,4	g/t	20	0,00002	15,2	1,8	1-3
CF4	*0,13*	*0,37*	*kg/t*	*100*	*0,005*	*2,6*		
C2F6	*0,013*	*0,046*	*kg/t*	*100*	*0,0004*	*0,40*		

*per t aluminium

Table 4a

IAI LCS 2005: ingot casting

Inputs

Life Cycle Survey	**Total production: 12221273 t**		Est. survey coverage of total world production:
	No. of cast houses: 48		**44%**
IAI Energy Survey	***Total production: 17816935 t***		*Est. survey coverage of total world production:*
	No. of cast houses: 80		***64%***

Inputs

DQI = year 2000 data

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Electrolysis metal	955	259	kg/t	85	0,8	1403	1,0	1-2
Remelt ingot	100	119	kg/t	46	0,6	546	1,2	1-3
Outside scrap	43	84	kg/t	54	0	331	1,1	1-3
Alloy additives	19	16	kg/t	73	0	66	1,1	1-3
total	1117		kg/t					
Fresh Water	5,1	6,9	m3/t	35	0,06	26	1,6	1-3
Chlorine	0,041	0,14	kg/t	48	0	0,58	1,3	1-3

*per t aluminium ingot

Fuels and electricity

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max
Heavy Oil	*5,7*	*31*	*17*	*kg/t*	*23*	*1,0*	*66*
Diesel oil	*1,4*	*9,4*	*25*	*kg/t*	*20*	*0,1*	*86*
Gas	*30,0*	*37*	*34*	*m3/t*	*75*	*0,1*	*166*
Coal	*1,2*	*48*		*kg/t*	*1*	*48*	*48*
Electricity	*83*	*100*	*91*	*kWh/t*	*85*	*0,002*	*427*

*per t aluminium ingot

Note: metal input adjusted to exclude contribution from cold metal (see section 2.3 reference flow)

for 1000 kg ingot output

		adjusted to	unit*	
Electrolysis metal	955	1000	kg/t	share of ingot casting inputs and outputs
Alloy additives	19	20	kg/t	for primary aluminium Life Cycle calculation
total	974	1020	kg/t	0,88 (= 974/(1117-8.4))

Table 4b

IAI LCS 2005: ingot casting

Outputs

Life Cycle Survey — **Total production:** 12221273 t — No. of cast houses: 48

Est. survey coverage of total world production: 44%

Product: aluminium ingot 1000 kg

Water Discharges — DQI = year 2000 data

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Fresh Water	5,6	7,5	m3/t	29	0	26	1,7	1-3
Suspended solids	0,026	0,093	kg/t	4	0,003	0,13	1,8	1-3
Oil & grease/total HC	0,011	0,021	kg/t	6	0,0002	0,038	1,9	1-3

*per t aluminium

By-products for external recycling — DQI = year 2000 data

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Dross	13,3	7,5	kg/t	73	1,8	33	1,04	1-3
Filter dust	0,63	1,7	kg/t	23	0	4,9	1,2	1-3
Scrap sold	8,4	19	kg/t	42	0	76	1,1	1-3
Refractory	0,24	0,63	kg/t	35	0	2,6	1,4	1-3

Solid waste not recycled — DQI = year 2000 data

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Dross	2,5	7	kg/t	58	0	28	1,3	1-3
Filter dust	0,15	0,3	kg/t	21	0	1,0	1,6	1-3
Refractory	1,2	3,8	kg/t	27	0	14	1,7	1-3
Other landfilled waste	0,21	0,32	kg/t	8	0,00	0,7	1,7	1-3

*per t aluminium

Table 4c

IAI LCS 2005: ingot casting

Outputs — Air emissions

Life Cycle Survey — **Total production:** 12221273 t — No. of cast houses: 48

Est. survey coverage of total world production: 44%

DQI = year 2000 data

Air emissions	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Particulates	0,048	0,10	kg/t	54	0,0003	0,42	1,5	1-3
SO2	0,035	0,046	kg/t	23	0,0006	0,16	1,9	1-3
NOx (as NO2)	0,11	0,09	kg/t	23	0,009	0,28	1,9	1-3
HCl	0,010	0,034	kg/t	27	0	0,12	1,7	1-3
Dioxin/Furans	0,00024		mg/t	2	0,00024	0,00024	2,5	1-3

*per t aluminium

Appendix C: CO_2 emission data

The CO2 equivalent table below is based on collected data on material input and production, fossil fuel and electricity consumption (including the source of electricity, whether hydro, coal, gas, oil or nuclear) CO2 conversion factors published by the International Energy Agency, the IAI 2005 PFC report and the IAI GHG protocol. For the full calculations please contact: bertram@world-aluminium.org

Results show that for 2005 per tonne of aluminium 9.8 tonnes of CO2 equivalent are emitted. This includes scope 1 (process) and scope 2 (electricity). Scope 3 emissions (transport and ancillary) would need to be added, which amount to about 0.7 tonnes of CO2 equivalent per tonne of aluminium.

All figures in kg of CO2e

	Bauxite Mining	**Alumina Refining**	**Anode Production**	**Primary Smelting**	**Primary Casting**	**Mine to Ingot**
	kgCO2e/ 1000kg Bauxite	kgCO2e/ 1000kg Alumina	kgCO2e/ 1000kg Anodes	kgCO2e/ 1000kg Aluminium	kgCO2e/ 1000kg Primary Ingot	kgCO2e/ 1000kg Primary Ingot
Process	0	0	402	1557	0	**1763**
Electricity	1	64	66	5225	42	**5529**
Fossil fuel	4	707	150	0	82	**1530**
PFC	0	0	0	970	0	**989**
Total	**5**	**771**	**617**	**7752**	**125**	**9812**
Factor	5,272	1,923	0,435	1,02	1,00	

Appendix D: Further reading

EAA, 2007. Environmental Profile Report and Aluminium Recycling in LCA. Reference year 2005. Note: Includes life cycle inventory data for rolling mills, extruders and recycling.

EAA, 2007 update. Aluminium Recycling in LCA. www.eaa.net Brussels, Begium