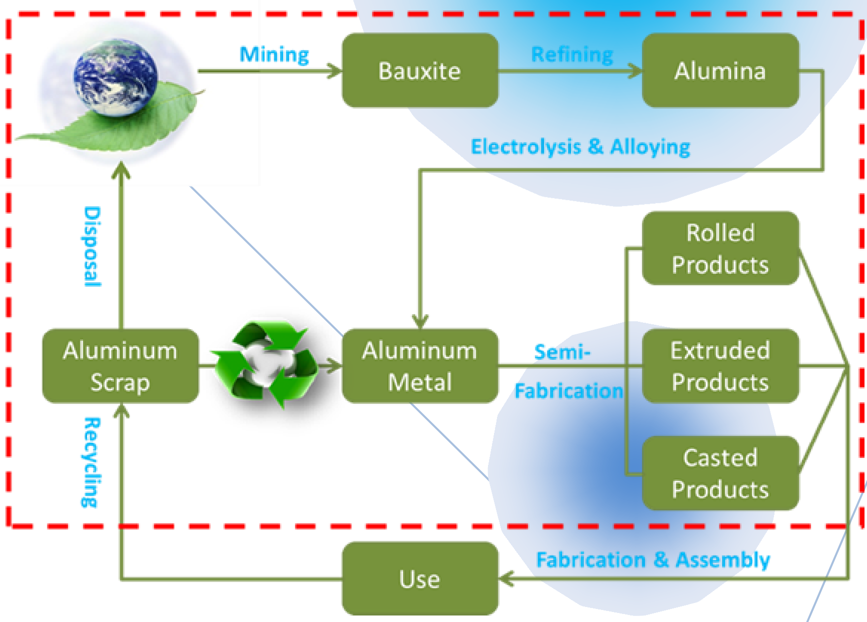

The Environmental Footprint of Semi-Finished Aluminum Products in North America

A Life Cycle Assessment Report

The Aluminum Association

December 2013

Table of Content

0. Introduction

0.1 Life Cycle Approach

The traditional approach to the environmental management of industries and businesses largely focuses on facility-level compliance and control. This approach addresses only a single stage in the life-cycle of a product (including service) and therefore only a small proportion of the larger system (Azapagic et al, 2004). This approach is inadequate because a product or industrial activity exists not in isolation but rather as part of a complex system (Graedel et al, 2003).

This larger system refers to all the stages in a product's life-cycle, including raw material extraction and processing; product design and manufacturing; packaging and delivery; use and maintenance; and reuse, recycling and/or disposal. The dynamic interaction of each life-cycle stage with the environment is shown in **Figure 1**. This diagram displays only the interaction with the environment; the addition of economic and social systems further increases the complexity.

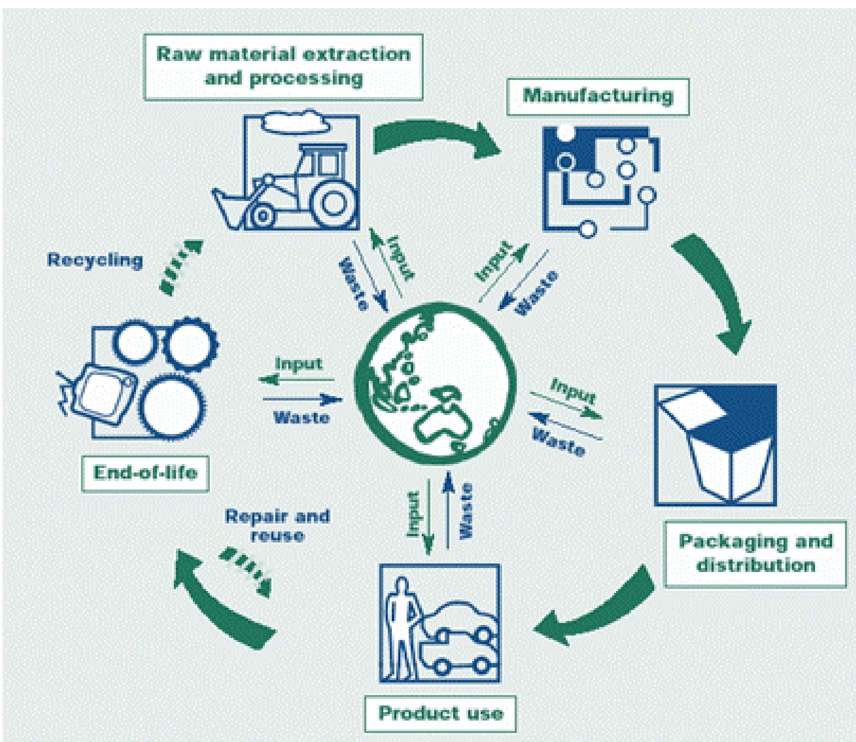

Figure 1: Product life cycle stages and the interactions with the environmental system (Picture adopted from UNEP Guide to Life Cycle Management, UNEP 2005. The original source of the picture was from Australian Department of Environment and Heritage)

To address system complexity, the entire life-cycle of the product must be considered ("life-cycle thinking"). A decision made based on life-cycle thinking is called "life-cycle approach."

Life-cycle approach is a system approach in product sustainability management taking into consideration the production of a product, consumption and end-of-life management. Life-cycle approach avoids the issue of shifting, i.e., problems that shift from one life-cycle stage, one location, one time, or one generation to another (UNEP, 2005); it transcends the traditional boundaries of single-stage focus and makes it possible to address all three aspects of the triple-bottom-line—economic, environmental and social—at the same time.

0.2 Life Cycle Assessment

An important tool in environmental management based on life-cycle approach is life cycle assessment (LCA). LCA is a methodology that uses a system approach to understand the potential environmental consequences of a product, process or activity from initial extraction of raw materials from the earth until the point at which all residuals are returned to the earth. The goal of LCA is to quantify, evaluate, and then identify opportunities to reduce the overall environmental effects of the system under study.

The LCA methodology, as defined by International Organization for Standardization (ISO) 14040/44, is typically divided into four separate and interrelated components:

- Life Cycle Scope and Goal Definition includes the clear statement of the purpose of the study; the system to be studied; the intended use of the results; limitations on its use for other purposes; data quality goals; reporting requirements; and the relevant type of review process. The scope also defines a description of the geographical and temporal boundaries, system boundaries; data requirements; decision rules; and other assumptions.
- Life Cycle Inventory Analysis (LCI) is the phase of LCA involving the compilation and quantification of inputs and outputs through the live cycle of a product or service, including the stages of resource extraction, manufacturing, distribution, use, recycling and ultimate disposal.
- Life Cycle Impact Assessment is the phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system.
- Life Cycle Interpretation is the phase of the LCA technique in which the findings of the inventory analysis and impact assessment are combined together in line with the defined goal and scope. The findings may take the form of conclusions and recommendations to decision-makers, consistent with the goal and scope of the study.

0.3 History of The Aluminum Association's LCA Studies

During the past two decades, the Aluminum Association has sponsored three major LCA studies.

- The first study was carried out in 1992 and completed in 1993. It examined the cradle-to-grave life-cycle inventories of the 12-ounce aluminum beverage can (product use-phase excluded). The base year of the study (the year the production information was collected) was 1991.
- The second study, carried out in 1996 and completed in 1998, examined the cradle-to-grave life-cycle inventories for automotive products (final auto part fabrication, assembly and product use-phase excluded). The base year of the study was 1995.
- The third study, carried out in 2007 and completed in 2010, concentrated on a cradle-to-grave life-cycle inventory assessment of a mixture of aluminum beverage cans (beverage filling and product use-phase excluded). The base year of this study was 2006 (with primary metal production representing the 2005 production year).

These LCA studies have helped the industry and its stakeholders understand in great details the products of aluminum and their potential environmental impacts, enabling informed decision making and the identification of areas for improvements by the aluminum industry. They also helped the general public learn more about the pros and cons of man-made materials and the overall benefits of such materials brought to the well being of human's life, thus enabling them to make their individual contributions to the sustainable development society by reuse and recycle products as much as possible.

0.4 About This Study

However, the aluminum product system is a dynamic one in which processes and technologies involved are constantly changing. Being able to monitor such changes and evolutions through continuous LCA studies is a critical strategy of the industry and it is highly in lined with the sustainability commitment made by the industry.

Under a 2008 Sustainability Initiative, the Aluminum Association has launched several technical study projects in which one of them is the updating and expansion of the 1998 life cycle inventory study of automotive aluminum products. The updating is aimed at providing the most up-to-date life cycle inventory information for aluminum products and the expansion is aimed at including generic semi-fabricated aluminum products shipped to other market sectors such as building & construction, packaging, consumer durables, as well as other means of transportation than automobiles. The expansion is also aimed at providing Life Cycle Inventory Assessment results.

This report documents the processes and findings of the LCA project. The report is structured as follows:

- A brief description of the aluminum product systems
- A goal and scope definition of the study
- A documentation of data collection and data processing
- A description of data presentation methods
- A life cycle inventory analysis and life cycle impact assessment, and
- Conclusion and interpretation

1. The Life Cycle of Aluminum Products

The typical life cycle of aluminum products starts with resource extraction (cradle) and ends up with disposal or recycling (grave/cradle). This life cycle can be depicted from **Figure 2**:

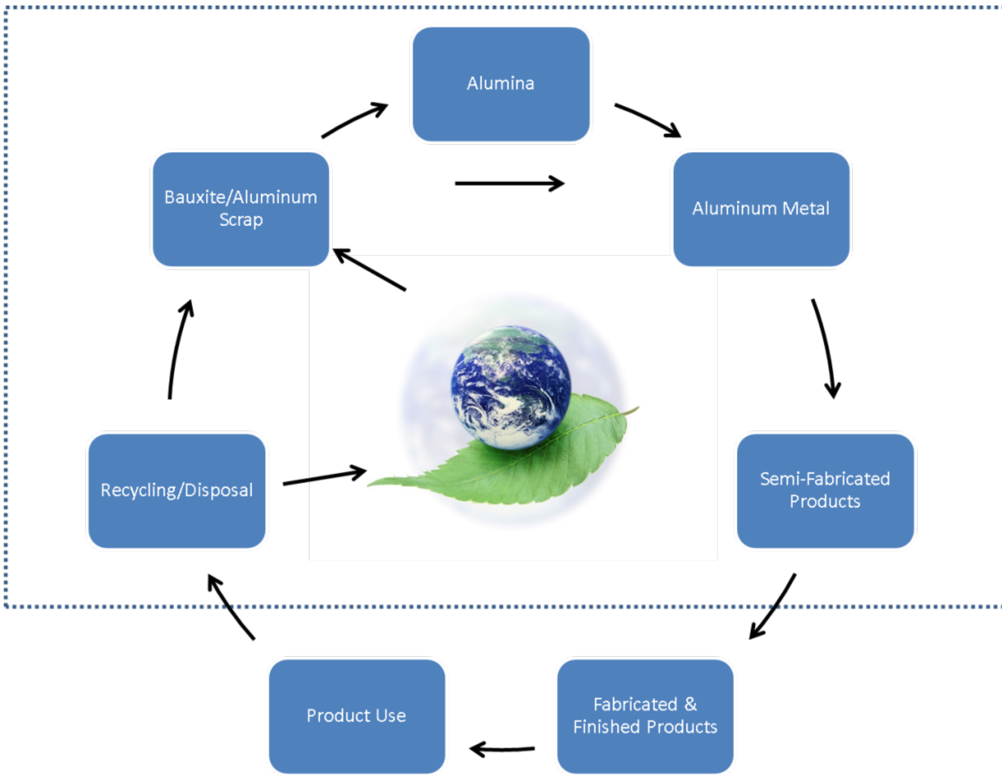

Figure 2: the life cycle of aluminum products.

It is generally considered that the aluminum industry is the industry that involves in partial or all activities inside the enclosed life cycle stages while the aluminum product users involve in the non-enclosed two life cycle stages. In North America, the industry involves mainly in metal production, product semi-fabrication, and recycling.

There are two distinctive routes of aluminum production: from natural resources – a special rock called bauxite, and from man-made resources – aluminum scrap. Theoretically, metals made from these two different resources share the same properties and perform the same functions. From an environmental footprint point of view, however, there are significant differences.

When aluminum is made into metal, which is normally in alloy forms, it is going through a semi-fabrication and fabrication/finishing process to be turned into usable products. The product use phase can be as short as a couple of months, or it can be as long as more than a century. At the end of the product's life, it is usually recycled into new metals, or in some cases disposed into landfills – returning to the natural environment.

Most of the environmental burdens of aluminum products incur at the resource extraction, raw material production, and product semi-fabrication stages. On the other hand, like all manufactured products, tremendous social, economic and environmental benefits can be gained at the product use stage. The product fabrication and finishing stage incurs some environmental burdens but the level is normally very small compared to the total life cycle burdens for most of the products.

2. Goal and Scope Definition

2.1 Goal of the Study

The primary purpose of the study is to update a 1998 semi-fabricated automotive aluminum product LCI study and expand it to include all major categories of generic semi-fabricated aluminum products (extruded, flat-rolled, and shape-casted) shipped to all market sectors including transportation, packaging, building and construction, and consumer durables. The study shall generate high-quality and up-to-date LCI data and information for all purpose of life cycle assessment studies involving relevant aluminum parts and/or products.

The update of the LCI became necessary as the original LCI became increasingly out of date - partly due to technological changes and partly due to the fact that the original LCI could no longer meet the information needs of the 21st century society. The updated LCI shall reflect the current technological situation, production practices, as well as the average North American market situation.

With such an updated LCI database, the Aluminum Association and its member companies can assist other organizations to better understand and communicate the environmental benefits of manufacturing with aluminum. At the same time, this database will help the industry improve understanding of its manufacturing processes, and identify potential areas for improvements. Such evolutionary process of understanding – identification – improvement is a fundamental commitment of the industry in its sustainability movements.

In addition, the study is intended to provide life cycle impact assessment (LCIA) results to meet the increasing information needs from aluminum product stakeholders including manufacturers, users, consumers, government agencies, academia, and the general public.

2.2 Intended Audience

The intended audience for this study is the Aluminum Association itself, the potential customers and decision makers in industry, LCA professionals and practitioners, as well as the general public. The Aluminum Association experts will use the information from this study in an aggregated manner for public communications, to develop marketing materials for potential customers and to provide data to customers for the purpose of developing LCIs within their own applications.

2.3 Use for the Study

Among other things, the results of the study can be applied to:

- Establish an up-to-date LCI database for semi-fabricated aluminum products in North America. Such a database can assist the aluminum industry and its stakeholders in a variety of LCI data designated applications;

- Improve understanding of the potential environmental implications of product manufacturing and the overall life cycle burdens and benefits of aluminum products;
- Facilitate the assessment of alternative production design options (for instance, alternative process design, technology, etc.), compare corresponding datasets, and guide the evaluation of modifications for improvement;
- Provide information for use in strategic planning and sustainable development;
- Develop communication messages such as Environmental Product Declarations (EPDs) and industry sustainability reports.

2.4 Limitations for Use

Life cycle assessment is a modeled approach based on specific assumptions. The Aluminum Association reorganizes the potential for misuse of the LCA data and information by users. **For instance, there have been cases in which competitive industries use the primary energy demand (PED) and global warming potential (GWP) associated with per kilogram/pound of primary aluminum metal production to compare with those of a kilogram/pound of other material production to establish claims of the environmental "superiority" of their own materials.** Such misuse is not only detrimental to the aluminum industry, but also extremely misleading for the general public.

Therefore, it is noted here that the updated inventory database and the study results shall not be:

- Used as the sole criteria in raw material or product selection decisions;
- Partially, selectively, or inappropriately used to claim against the aluminum industry and its products;
- Used as a base for federal, state and/or local level government environmental regulations against the manufacturing activities of the aluminum industry.

2.5 Product Systems under Study

The product system under study is the enclosed life cycle stages in **Figure 2**. To be specific, it is the processes and life cycle stages depicted in **Figure 3**. Note that the use stage is not included in this study. Also not included is the "fabrication & assembly" process.

The major categories of products included in the study are:

- Primary metals
- Secondary/recycled metals
- Flat-Rolled Products (sheet and plate, excluding foil)
- Extruded Products
- Shape-Casted Products

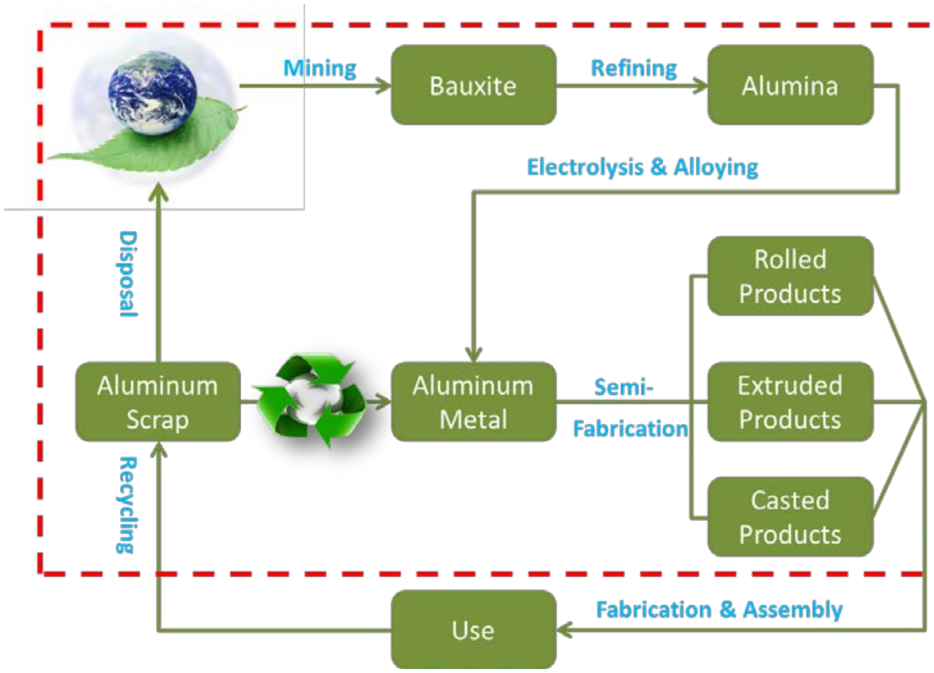

Figure 3: life cycle stages included in this study.

2.6 System Boundaries

The products being examined are generic semi-fabricated aluminum products. To be specific, it includes extruded, flat-rolled, and shape-casted products. The physical property of these products, their manufacture and impact represent the current technological situation in the North American market. The products may be further processed and assembled before use but the fabrication and assembly are not included in this study. The system boundaries are summed in **Table 1**:

Table 1: Summary of system boundaries

Included	Excluded
• Raw materials extraction • Energy and fuel inputs • Extraction, processing and delivery of energy and the fuel inputs • Extraction and processing of auxiliary materials (e.g. chemicals, solvents, lubricants, packaging etc.) • Production of the metal and processing it into semi-finished products • Product surface treatment and finishing (e.g. anodizing, coating etc.) • Transportation of raw and processed materials and products • Product recycling • Waste treatment and disposal • Overhead (heating, lighting) of manufacturing facilities	• Capital equipment and maintenance • Maintenance and operation of equipment • Human labor • Pre-use fabrication and assembly • Use of product

2.7 System Function and Functional Unit

The function of the products is to serve as individual components, parts, units or integrated products to be used for transportation, building and construction, packaging, consumer durables, electrical, or other purposes.

The functional unit for this study is to model for one thousand kilogram (one metric ton) of each category of products including:

- primary metal
- secondary/recycled metal
- extruded (extrusion),
- flat-rolled (sheet and plate), and
- shape-casted (casting).

2.8 Geographic Coverage

The geographic coverage is North America including Canada, the United States and Mexico.

Due to the reality that responses from Mexico on some of the surveyed product systems were not enough to represent the industry in the country, and that the supply chain of the aluminum semi-fabrication industry (i.e. metal producers, alumina refiners, bauxite miners, and scrap collectors and processors) covers not only North America but also the rest of the world in many cases, specific coverage for specific manufacturing processes is summed in **Table 2**:

Table 2: Geographic coverage of this study, by life cycle stages:

Life Cycle Stage	Major Unit Process	Geographic Coverage
Primary Metal Production	Bauxite Mining	World
	Alumina Refining	North America and Rest of World
	Anode Production	World
	Aluminum Smelting	Canada and USA
	Electricity Generation	For the smelting and ingot casting processes, it is the aluminum industry specific power mix based on power contracts and self-generation capacities, representing all smelters in Canada and USA; for other processes, it is the average grid mix of the relevant production country or region.
Secondary Metal Production/Recycling	Scrap Collection and Processing	North America
	Metal Production	North America
	Electricity Generation	Specific power source of most individual facilities can not be tracked. Therefore,

		average gird mix of the country, Canada or USA, is used.
Semi-Fabrication	Extrusion	North America
	Flat-Rolling	Canada and USA
	Shape Casting	North America
	Electricity Generation	Specific power source of most individual facilities can not be tracked. Therefore, average gird mix of the country, Canada, USA or Mexico, is used.

2.9 Time Period Coverage

The designated time period coverage for this study is 2010. Primary data collected from the participating companies and for their operational activities are representative for the year of 2010 (reference year). Additional data necessary to model raw material production and energy generation, etc. were adopted from the GaBi 6.0 software system database.

During the survey, however, a small group of semi-fabrication facilities have reported operational data for 2008, 2009, or 2011, depending on the time when they started to respond to the survey and the convenience of their data availability. This deviation from the defined reference year has been taken into account as it is being assumed that there are no radical changes in the technology and operational practice for semi-fabrications from the year 2008 to 2011.

2.10 Technology Coverage

The study covers the currently operational aluminum production and fabrication technology mix with an exception that the shape casting only covers one technology category – die casting.

3. Data Collection, Software, and Database

3.1 Data Collection

The goal of the study is to generate LCI data and LCIA results that can represent the current average production situation of the examined product systems in North America. In achieving this goal, primary operational data directly coming from manufacturing facilities is preferred than secondary and third data. In collecting primary operational data, several steps have been carried out to determine the data survey targets.

3.1.1 Data Collection Procedures

The first step is to decide the source of data collection for different life cycle stages. Major life cycle stages involved in this study include raw material extraction (bauxite mining and alumina refining), primary metal production, secondary/recycled metal production, semi-fabrication and finishing, and end-of-life management (recycling and disposal).

- Among these stages, data for raw material extraction and primary metal production was collected through the International Aluminium Institute (IAI). IAI directly collects data and information on an annual basis from bauxite mining companies, alumina refining facilities and primary aluminum production facilities across the globe, including all North American facilities. Aggregated IAI datasets representing North America can be directly transferred to the Aluminum Association.
- Data of secondary aluminum production, semi-fabrication, and recycling can be directly collected by the Aluminum Association from relevant manufacturing facilities in the North American region.

The second step is to look into the Aluminum Association's database to identify all aluminum producers, semi-fabricators, and recyclers in the region. Due to the very large number of manufacturers and individual facilities involved, it is essentially impractical as well as unnecessary to survey all players.

For this reason, the third step is to select survey samples from the entire pool. Random selection technique was used to ensure the representativeness of samples for the industry. As a result, a total of 97 companies and 319 facilities were selected in the sample. The sample represents about 90% of the industry's overall production capacity in each of the product groups. The majority number of companies selected for survey samples are small companies focusing only on semi-fabrication activities.

The fourth step of data collection is to conduct survey. This includes survey form distribution, response collection, data quality checking, and data aggregation. This is the longest and most onerous step of the entire project. Due to the very large and diversified sample size as well as the lingering global economic recession that impacted almost all manufacturing industries, it took the Association 30 months (two and a half years) to complete this step, ended up with satisfactory response rates to represent the industry in the region in terms of recycling and secondary aluminum production, aluminum extrusion, and aluminum flat-rolling (sheet and plate production).

However, survey on aluminum shape casting ended up with failure and not enough response to represent the industry. For this reason, we choose to use data from commercial database to model the aluminum shape casting process.

3.1.2 Data Categories and Survey Forms

Operational data survey is based on distinctive unit production processes. Each unit production process is characterized and documented by a list of inputs and outputs as shown in **Figure 4**:

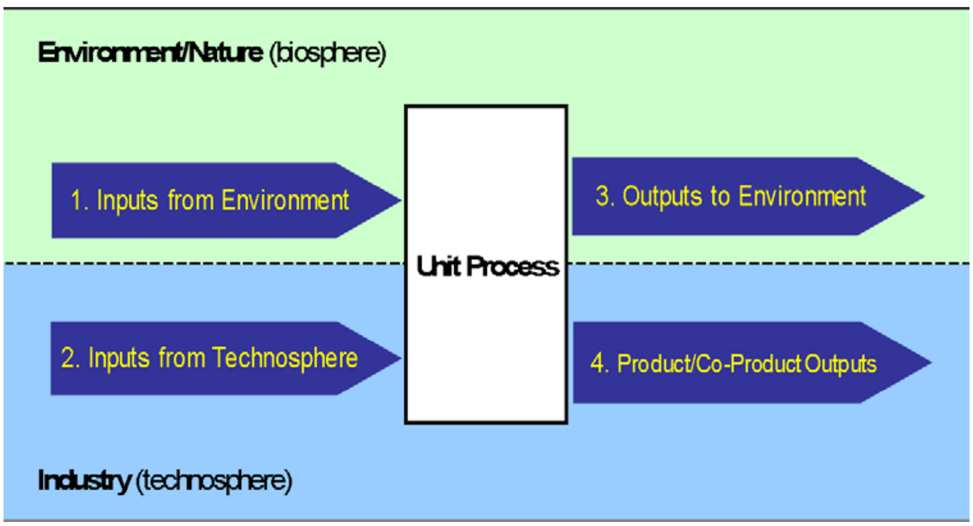

Figure 4: Life Cycle Inventory – Unit Production Process Template

In particular, the following data categories are predefined and included in the survey forms/questionnaires:

- Water inputs
- Energy inputs including all fossil fuels, non-fossil fuels, electricity, and purchased thermal energy (steam)
- Material inputs including major and auxiliary material inputs
- Product, intermediate product and by-product outputs
- Environmental releases including air, water and solid waste releases
- Waste treatment mechanism (e.g. treated, non-treated, recycled, landfilled, etc.)

In addition, data categories such as plant information, process description, source of raw and intermediate materials, market sectors of product use, and in-and-out transportation are also included in the survey forms. These additional information categories are designed to enhance and ensure data accuracy and completeness, use as baseline for industry benchmarking, and track errors of reporting.

It is worthwhile to point out that special attention is put on finding out the exact source of feedstock of metals used for semi-fabrication. In doing so, the raw material inputs category is specifically designed to track metal feedstock at the melting or re-melting furnaces. For instance, the Flat-Rolling survey includes the following categories of major material inputs for the metal melting and hot-rolling process:

- Processed old aluminum scrap, if any
- Processed new aluminum scrap, if any
- Processed mixed source aluminum scrap (purchased and source non-identified), if any
- Processed run-around aluminum scrap, if any
- Molten/liquid primary aluminum (hot metal from electrolysis pots), if any
- Molten/liquid secondary aluminum (hot metal from melting furnaces), if any
- Primary aluminum sow or ingot
- Secondary/recycled aluminum ingot (other than run-around scrap), if any
- Other aluminum ingot (specify)
- Alloy elements, if any

3.1.3 Format of Survey

Survey forms were intentionally designed in EXCEL spreadsheets for learning purposes. Such learning experience is essential both for the Aluminum Association and the participating companies and facilities. Through this learning experience, the industry will be able to increase the awareness of life cycle thinking among its manufacturers. It will also enable the Aluminum Association to design and develop better online survey tools for similar future studies.

Survey forms were distributed and collected through emails. Samples of original survey forms and questionnaires are included in Appendix 10.1 of the report.

3.1.4 Response Rate and Overall Coverage

As a result of the survey efforts, a total of 129 manufacturing facilities representing 25 companies responded the survey and provided data. This level of response, in terms of total tonnage of productions, represents the following industry coverage:

Table 3: Industry representation by product categories.

Product Categories	Total Producer Net Shipments (MT)	Reported Tonnage in Survey (MT)	Industry Representation (Percent)
Primary Metal	4,690,468	4,439,931	95
Recycled Metal	3,574,368	2,201,284	62
Extruded Products	1,224,720	723,116	59
Flat-Rolled Products (excl. foil)	3,415,608	2,921,182	85
Cast Products	1,750,000	n/a	n/a

It is important to point out that the coverage in each of the categories is defined as the fraction of the total producer shipments of the industry (statistical shipments) by the cumulative tonnage of productions reported by the reporting facilities. This coverage definition and calculation is fundamentally different from the common practices of most other industries, particularly material manufacturing industries.

It is our understanding that most trade associations, whether it be global, regional, or country level, conduct their life cycle assessment survey by cherry picking survey targets. It is a common practice among raw material industries to use data from one individual facility to represent a multi-facility and multi-national corporation. And it is not uncommon for some industries to pick one or two facilities to represent the entire industry.

3.1.5 List of Survey Respondents

A list of survey respondents is provided in Appendix 10.2. The list is in alphabetic order by company or corporation names. This list is provided for EPD verification purpose. Some of the companies have gone through merger and acquisition (M&A) processes since the survey. For that matter, the list reflects the latest names after the M&A processes.

Special attention shall be put that only names of parent corporations have been listed. Any individual aluminum product manufacturing companies who belong to these parent corporations should be covered by this study. For instance, Kawneer and Traco are subsidiaries of Alcoa Inc. Both companies participated in the survey and therefore shall be covered.

For most of the listed companies or corporations, all of their production facilities have participated in the survey. Only a small fraction of the listed companies have selected facilities to respond to the survey. This was done in order to encourage non-members of the Aluminum Association to participate in the survey.

3.2 Software and Database

There are additional critical auxiliary materials and production processes that are outside the aluminum industry. These include the production or processing of all relevant auxiliary materials, the production of fossil and non-fossil fuels, and the generation and transmission of electricity, among others. Also as stated previously, the survey of the aluminum shape casting process, although considered part of the aluminum industry, was failed due to a variety of reasons. Appropriate database is therefore needed to be used to get relevant LCI information. In addition, to perform life cycle inventory assessment, appropriate software must be used.

The GaBi software and its relevant database were adopted to carry out this study.

3.3 Data Calculation

In addition to the many assumptions that are made to simplify the data collection process, there are several special calculation procedures that are used to refine and integrate the information for the inventory of the industry. This section describes the techniques and calculations used in compiling the inventory.

3.3.1 Reporting Units

The reporting units are in line with the global convention of life cycle inventory and impact assessment reports which are unified to metric units. For instance, mass is in kilograms (kg) or metric tons (MT), liquid volume is in liters (L), gaseous volume is in cubic meters (Cu. M), and energy is in mega-joules (MJ). Other conventional metric units are also used in terms of electricity (kilowatt hours or megawatt hours, kWh/MWh), distance (meter or kilometer, m/km), concentration (e.g. ppm), etc.

The energy inputs by individual facilities were reported in the values of mass or volume during data survey. The conversion of mass and volume to calorific value was based on Lower Heating Value (LHV) by the GaBi software. The resulted primary energy demand was presented as net heating value.

3.3.2 Aggregation, Integration and Averaging

Given the sensitivity of original operational data from individual facilities and the legal obligation of the Aluminum Association in protecting such data from being disclosed to the public without prior writing agreement from relevant companies, surveyed data concerning the same product or process were aggregated, averaged, and presented in a fashion that ensures confidentiality of individual company information. The aggregated results (weighted-average numbers normalized for each unit production process) were sent to the LCI model developer (PE International) to calculate the life cycle inventory and perform the impact assessment. It should be noted that in no case did the Aluminum Association include data and/or summaries that will reveal the confidentiality of individual facility or company data. For example, for unit production processes where fewer than three companies participated, data was hidden. For benchmarking purposes, when desired and requested, the Aluminum Association will send to an individual data reporting company a set of confidential benchmark figures revealing the performance of the company within the context of the entire industry in the region.

A combination of vertical and horizontal averaging method has been used to derive the mean value of the primary operational data. The vertical method (see **Figure 5**) was applied consistently to all the companies as this method is more representative of actual industrial processes.

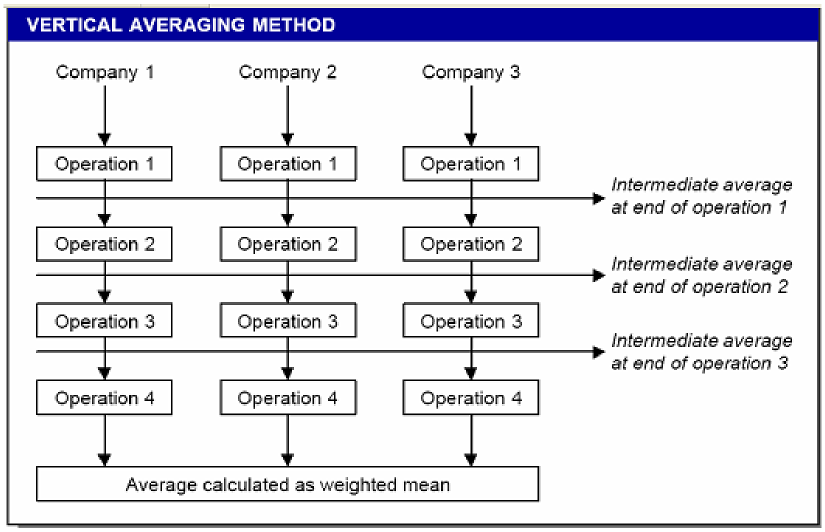

Figure 5: Illustration of the Vertical averaging method. The final average is calculated from a weighted mean of the sum of all the operations of each company. Intermediate averages may also be calculated after each operation (ECOBILAN, 2001).

However, in the case of identical processes in which certain data reporting is missing from a particular facility, the horizontal averaging method (see **Figure 6**) was used. The horizontal aggregation supports the modular approach which allows an easy combination of distinctive and consecutive production processes and gives details on the contribution of the various process steps to the complete LCI dataset.

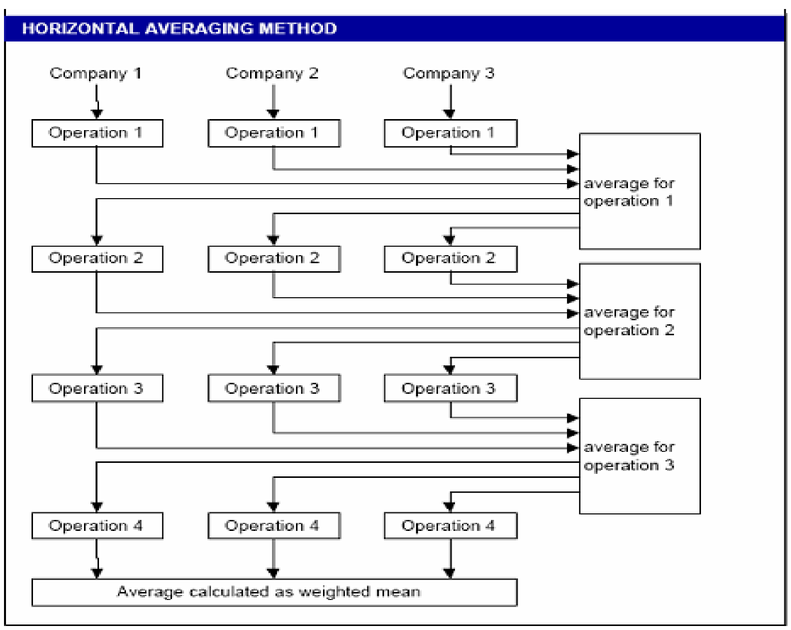

Figure 6: Illustration of the Horizontal averaging method. Averages are calculated after each operation and are used as the inputs for the next operation. In our context, this method is only used when a particular company does not produce an intermediate product or when there is insufficient data for an intermediate operation (ECOBILAN, 2001).

3.3.3 Allocation

Wherever possible, allocation has been avoided by expanding system boundaries. Each LCI dataset includes aluminum scrap, dross and recyclable salt cake recycling so that the only valuable products exiting the system are aluminum ingot or semi-product. The only allocation cases involve two ancillary processes automatically calculated by the GaBi tool:

- The production of caustic soda (NaOH used in the alumina production). In this case, NaOH and chlorine are simultaneously produced from the Solvay process. The proportion of inventory allocated to NaOH is on a mass basis.
- The production of electricity with co-generation of steam. In this case, allocation is based on the exegetic content.

The end-of-life allocation was done by taking an Avoided Burden approach. Detailed explanation of this allocation method is given in Section **4.1**.

The incineration of non-hazardous solid waste is considered as energy recovery (thermal and electricity). To avoid any allocation, such energy is directly re-introduced in the LCI model and the energy input is reduced accordingly. In any case, such energy input from incineration is very limited (less than 0.01%).

3.3.4 Cut-Off Criteria

The following cut-off criteria were used to ensure that all relevant environmental impacts were represented in the study:

- Mass – If a flow is less than 1% of the cumulative mass of all the inputs and outputs (depending on the type of flow) of the LCI model, it may be excluded, provided its environmental relevance is not a concern.
- Energy – If a flow is less than 1% of the cumulative energy of all the inputs and outputs (depending on the type of flow) of the LCI model, it may be excluded, provided its environmental relevance is not a concern.
- Environmental relevance – If a flow meets the above criteria for exclusion, yet is thought to potentially have a significant environmental impact, it will be included. All material flows which leave the system (emissions) and whose environmental impact is higher than 1 % of the whole impact of an impact category that has been considered in the assessment, is covered.
- The sum of the neglected material flows shall not exceed 3% of mass, energy or environmental relevance.

3.3.5 Treatment of Anomalies and Missing Data in the Survey Reports

Anomalies are extreme data values within a reported dataset. Anomalies/missing data values are a result of misinterpreted requests for data input, misreported values, improper conversion among different units, or simply not available from a reporting location.

Anomalies and missing data of the survey reports were identified and communicated with reporting facilities. Verifications and, revisions in the case of misreport, were received and incorporated into the original reports. Where an anomaly was traced to process irregularities or accidental release, it was included in the dataset. If an explanation could not be found, the anomaly was removed from the dataset.

Data quality assessment is summarized in Appendix **9.3**.

When all attempts to secure actual and accurate data inputs from reporters were exhausted while the necessary data points are still abnormal or missing, a calculated value was used based on the average reported values from unit process with similar technology. Such corrections on individual facilities do not exceed 5% of the total reported data points.

3.4 Division of Tasks and Responsibilities among Involved Parties

This study involved three major parties: the manufacturing companies and facilities, the Aluminum Association, and PE International.

The manufacturing companies and facilities are responsible for providing their measured production data including inputs, outputs, and environmental releases.

The Aluminum Association is responsible for design survey forms, collecting survey data and aggregating survey data. It is also responsible for drafting the reports.

PE International is responsible for setting methodologies and carrying out the modeling tasks. It is also responsible for reviewing and revising the reports wherever appropriate.

3.5 Critical Review

The results of the LCA study are intended to support external communication; therefore in order to be compliant with ISO 14044, a critical review of the study was conducted.

The goal and scope of the critical review is defined in accordance with ISO 14044, paragraph 6.1. Following ISO 14044, the critical review process shall ensure that (ISO, 2006b):

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

The review of this study was done by both the Sustainability Working Group (SWG) of the Aluminum Association and an independent review panel. The SWG is comprised of the following members:

- Kenneth Martchek, Chair of SWG, Alcoa Inc.
- Casey Wagner, Alcoa Inc.
- Jessica Sanderson, Novelis Inc.
- Jean-Philippe Rheault, Rio Tinto Alcan
- Doug Richman, Kaiser Aluminum

The independent review task was organized and carried out by UL Environment and the review was part of the verification process for Environmental Product Declarations. The chief reviewer was:

- Thomas Gloria, Managing Director, Industrial Ecology Consultants

Communications between the critical reviewers and the project team allowed the integration of critical review feedback into the structure of the study, and the drafting and finalization of this final report.

4. Methodology and Data Presentation

4.1 Methodology

The study is both a life cycle inventory documentation and a life cycle impact assessment. As a result of the study, “cradle-to-gate” LCI and LCIA information is provided for all relevant intermediate and final product systems starting with the extraction of bauxite ore at the mines, and/or scrap collection at the various previous-generation aluminum product retirement sites.

In addition, “cradle-to-grave” (**excluding pre-consumption fabrication, assembly and the use phases**) LCIA results are provided for each of the final aluminum product systems under the study – **extruded, hot-rolled, cold-rolled (excluding aluminum foil), and shape-casted,** starting with resource extraction and ending with the recovery and recycling of post-consumer scraps.

The methodology used for goal and scope definition, data collection, inventory analysis, and impact assessment in this study is consistent with the methodology described in the ISO 14040 and 14044 Standards documents.

A Substitution Approach, also called Avoided Burden Approach, has been taken to calculate the cradle-to-grave LCIA.

The Substitution Approach is a recommended approach by the aluminum industry. The approach was endorsed and recommended by the worldwide metals industries including aluminum (John Atherton et al, 2007). Prominent institutions such as Yale University’s Stocks and Flows Project (Beck et al, 2012) and the UNEP International Resource Panel’s Working Group on Global Metal Flows (UNEP, 2011) also endorse taking an end-of-life (EOL) recycling approach.

The recommendation of the Substitution Approach is based on the characteristics of aluminum products and aluminum recycling, which preserves the full physical properties of the metal without losses of quality no matter how many times it is recycled. The aluminum recycling system is a semi-closed-loop system in which the recycled aluminum could end up with the same product system, e.g., extruded to extruded products, flat-rolled to flat-rolled products, and shape-casted to shape-casted products, or in other cases, the recycled aluminum from one product system could be used for other product systems depending on the efficient allocation of aluminum scraps by market forces.

The Substitution Approach also reflects the fundamental sustainability and environmental visions of the industry in North America, which focus on minimize the environmental and social cost of aluminum production, maximize the overall benefits of aluminum products brought to society, and preserve as much as possible the metal at the end of its useful life for future generations (**Figure 7**).

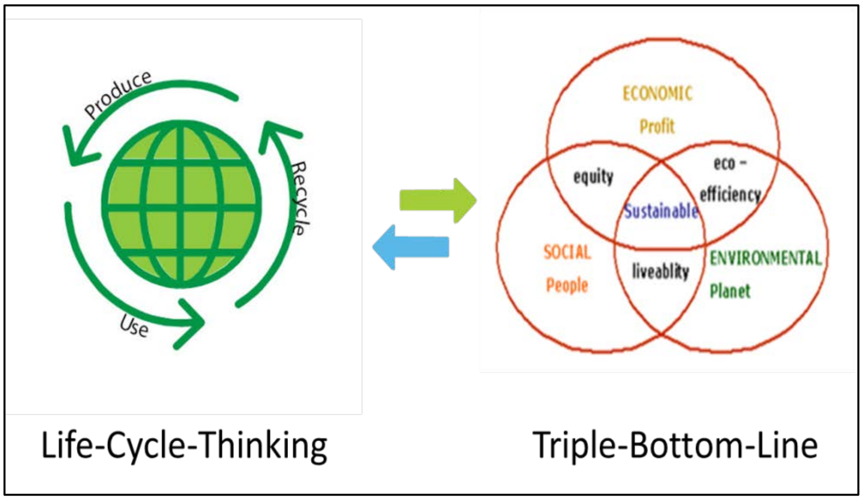

Figure 7: Sustainability vision of the aluminum industry in North America

On the other hand, the Aluminum Association also acknowledges that there are different methodological approaches exist in examining the environmental impacts of a product during its life cycle. For this reason, the Association takes a **complete transparency approach** to provide necessary information to accommodate users who wish to use their choice of appropriate methodology to conduct their own analysis. Given the fact that other methodologies may require recycled material content information, industry average metal feed stock information at semi-fabrication mills is provided for each category of products in terms of primary metal, internal process scrap, pre-consumer scrap, and post-consumer scrap.

The system flow chart for Substitution Approach is presented below in **Figure 8**. The approach is based on a product life cycle and material stewardship perspective. It considers the fate of products after their use phase and the resultant material output flows. In evaluating the environmental impacts of a product system using this approach, the EOL management of the product is taken into account and therefore, possible changes to improve the system can be considered. The specific origin of input material, e.g. primary or secondary, is irrelevant as typically the net conservation of material is what minimizes the total environmental impacts.

Under this framework, the product being examined is considered to be completely recycled once it reaches the EOL phase. Material losses are taken into account during the collection and processing of scrap as well as those associated with the production of secondary material (the melting and/or re-melting process). The lost material is replenished with the primary material to keep the system closed. Consistent with ISO 14044, the net recovered metal is considered to be a substitution of the same amount of primary metal and therefore help avoid the burdens associated with the primary metal production. A credit is given for such a substitution.

A designer using this approach focuses on optimizing product recovery and material recyclability. By facilitating greater end-of-life recycling, the decision-maker mitigates the loss of material after product use. This approach assesses the consequences at the "grave" stage of the product based on established technical practices, and supports decisions for an efficient market. **This concept allows design for recycling**.

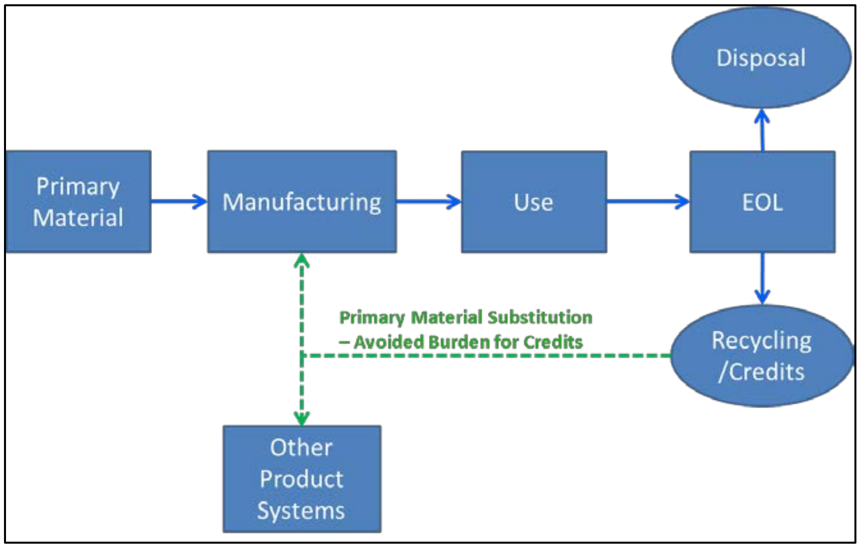

Figure 8: Process flow chart for a Substitution Approach.

4.2 Data Presentation

Aggregated input and output data, primarily generated out of direct survey results, is presented for each of the production unit processes. Brief process descriptions, together with boundaries, assumptions and flow charts of the process model, are provided. Data quality assessments are included where possible.

Cumulative LCI (on selected resources and emissions) is presented at the end of each major section for the following intermediate and final product systems:

- primary ingot;
- secondary ingot/recycled metal;
- extruded aluminum;
- hot-rolled aluminum;
- cold-rolled aluminum;
- cast aluminum

A total of 11 major production unit processes are identified. These include:

- bauxite mining;
- alumina refining;
- aluminum smelting (electrolysis);
- aluminum ingot casting;
- scrap collection and processing;
- secondary metal production (recycling);
- dross and saltcake recycling;
- semi-fabrication – extrusion;
- semi-fabrication – remelting and hot-rolling;

- semi-fabrication – cold-rolling, and
- semi-fabrication – shape-casting

In addition, an auxiliary process on anode production is also identified as an essential unit process.

Data of each production unit process is presented in a gate-to-gate fashion as **Input and Output Tables**. For each of these datasets, it is classified into 5 categories, i.e.

- major material inputs;
- auxiliary material inputs;
- energy inputs (including electricity, fossil and non-fossil fuel use, transport, and/or purchased thermal energy);
- product and by-product outputs; and
- environmental releases and emissions.

For life cycle impact assessment (LCIA), it was determined during the scope development process that a comprehensive set of environmental impact categories were to be investigated. For the purposes of succinct communication of the study results, the following impact categories were determined to best represent the Aluminum Association's priorities in issues related to sustainability:

- Primary energy demand (PED), including energy from non-renewable and renewable energy sources,
- Global Warming Potential (GWP) (100 years; includes carbon dioxide (CO_2) and other greenhouse gas (GHG) relevant emissions),
- Acidification Potential (AP),
- Smog Formation Potential (SFP), and
- Eutrophication Potential (EP)

The meaning and significance of these impact categories is discussed in detail in the relevant sections of this report. The impact assessment results were calculated using characterization factors of Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), developed by the US Environmental Protection Agency (EPA) (TRACI 2.1). The TRACI is one of the most widely applied impact assessment methods in LCA studies around the world, particularly in North America.

Both cradle-to-gate and cradle-to-grave LCIA results are presented for the following product systems:

- primary aluminum ingots;
- secondary/recycled aluminum ingots;
- hot-rolled products;
- cold-rolled products;
- extrusion products; and
- shape casting products.

5. Inventory Analysis and Results

5.1 Primary Aluminum Production

This section describes the unit processes associated with primary aluminum ingot production. The following sub-sections cover descriptions of the processes being modeled, inputs and outputs of the processes, and presentations of LCI and LCIA Results for 1000 kg of primary aluminum ingots.

5.1.1 Process Descriptions and Models

The life cycle stages of primary aluminum ingot production includes the component processes of bauxite mining, alumina refining, electrolysis (including anode production and smelting), and primary ingot casting. A process flow diagram is shown in **Figure 9**. The initial raw material is bauxite ore and final product is primary aluminum ingot with intermediate products of alumina (aluminum oxide) and molten aluminum (liquid) metal.

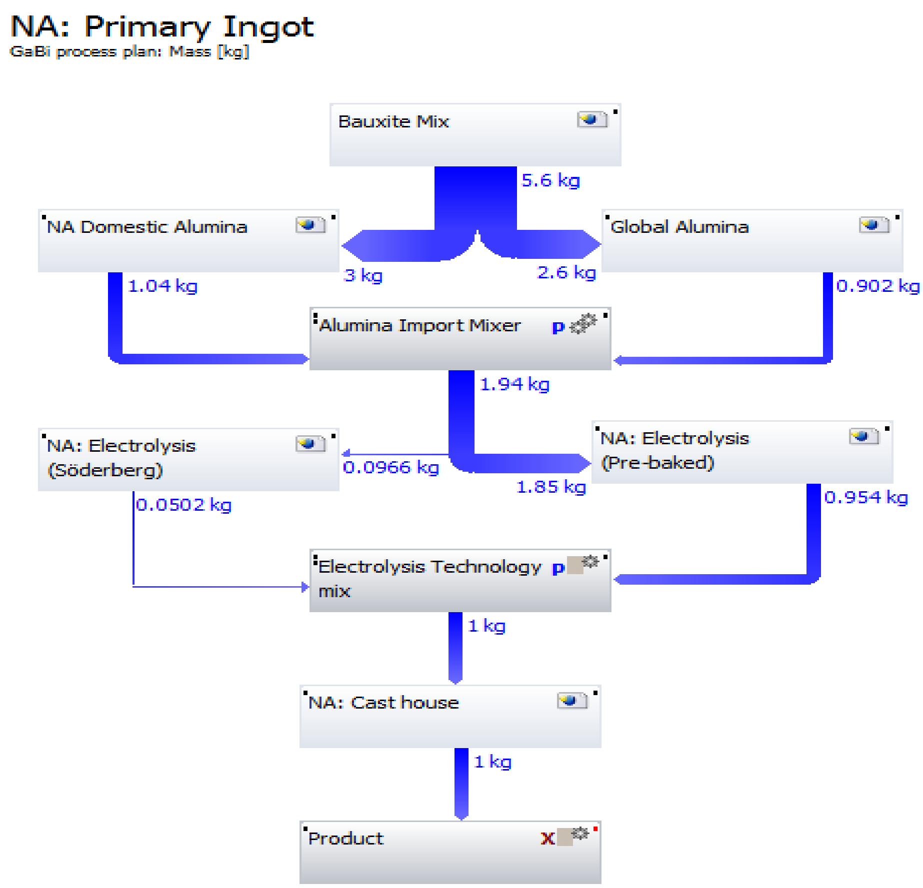

Figure 9: Process chain for the production of 1000 kg of primary aluminum.

In this study, the primary aluminum production in North America is modeled based upon primary data obtained from IAI. Sourcing of major raw materials in each of the unit processes is based upon statistical production, shipment and international trade data published annually by the Aluminum Association (AA), the U.S. Geological Survey (USGS), and the United Nations Comtrade Database (UN Comtrade). Sourcing of energy, particularly electric power in the smelting and ingot casting processes, is based on power contracts and on-site power generation capacities reported to IAI by individual facilities and companies.

Statistical data is treated as is in terms of data quality and accuracy. All data sources are official source that reflects the best understanding of the individual data providers.

The IAI dataset is a result of IAI's direct survey from bauxite mining, alumina refining, and primary aluminum smelting facilities around the world. The North America subset is a result of aggregated reporting from North American facilities. Therefore, the nature of this LCI dataset is the primary data in aggregated format. Overall, the data quality and consistency of the IAI dataset have been identified as of high quality.

The following sub-sections characterize the generic profiles for each of the unit production processes associated with primary aluminum and are based on the contents of similar previous studies carried out by the aluminum industry (e.g. AA, 1998; AA, 2010; EAA, 2008; IAI, 2007; IAI, 2013).

Each of the sub-sections is composed of three major components including:

- Unit process description
- Source of material and energy, and
- Unit process inputs and outputs

Illustrations of the **unit process models are also shown wherever necessary**.

Special attentions shall be paid by users on the unit process inputs and outputs. No carbon dioxide emissions from fuel consumptions are listed. For the calculation of the LCI and LCIA results, standard GaBi processes were used to calculate emissions. This approach guarantees that all emissions are accounted for correctly and accurately.

5.1.1.1 Bauxite Mining

5.1.1.1.1 Unit Process Description

Bauxite ore is the primary raw material source for aluminum production. Primary aluminum metal is almost exclusively produced from Bauxite. This ore consists primarily of the minerals gibbsite $Al(OH)_3$, boehmite, and diaspore AlOOH, together with minor fractions of iron oxides, clay minerals, and small amount of TiO_2. Bauxite is typically found at a depth of 0 to 600 feet beneath the earth surface, with an average depth of about 80 feet.

Bauxite is mined in open-pit mines by removing the overburden. The removed material is stockpiled for use in restoring the site after bauxite has been excavated. The bauxite deposit may be loosened by means of explosives, depending on its hardness and other local conditions. In some cases the bauxite is crushed in a grinding process using dust control equipment to prevent from excessive dust emission, and/or treated with water to remove impurities before it is shipped. This washing process is called beneficiation. Beneficiated bauxite will typically be dried prior to shipment to the refinery. The wastewater from washing is normally retained in a settling pond and recycled for continual use.

This bauxite mining unit process begins with the extraction and processing of the bauxite ore and it ends with the output of beneficiated bauxite to be refined in the subsequent process to produce alumina. The operations associated with this unit process include (AA, 1998; IAI, 2013):

- The extraction of bauxite rich minerals on-site,
- Beneficiation activities such as grinding, washing, screening, and drying,
- Treatment of mining site residues and waste, and
- Restoration activities such as grading, dressing, and planting.

5.1.1.1.2 Source of Raw Material and Energy

Nearly all bauxite consumed in North America was imported. Domestic bauxite mining is often negligible and most of it is utilized for non-metallurgical applications such as abrasives, chemical, refractory materials (USGS, 2011). Total metallurgical (i.e. to produce metallic aluminum) bauxite imports and the country of origin of imports in 2010 are given in **Table 4** and **Table 5**.

Table 4: 2010 North America bauxite imports for domestic alumina production (in metric tons). Data source: USGS, 2011; UN Comtrade, 2011.

Country/Region	Quantity
USA	8,120,000
Canada	3,373,000
NA Total	11,493,000

Table 5: Major source of bauxite imports to North America in 2010 [USGS, 2011] by country. It is assumed that Canada has the same source of importing as the US (data on Canada is not available).

Country	**Share of bauxite imports**
Jamaica	53.0%
Guinea	26.2%
Brazil	20.2%
Others	0.6%

It is worthwhile to point out that the situation of US bauxite importing (source of imports) was used to represent that of Canada since such data was not available for Canada. Such assumption would have minor effect on the total environmental footprint and would significantly simplify the overall model adopted for bauxite mining and thereby reduce possible errors and uncertainties.

Source of energy consumption for bauxite mining is correspondent with the countries where bauxite was mined and exported to North America.

5.1.1.1.3 Unit Process Model

As it is shown in **Figure 9**, there are two streams of bauxite introduced into the system in order to produce one metric ton of primary aluminum ingot – the proportion that is directly imported by North American alumina facilities, and the proportion that is imported as alumina. The bauxite mining model is based on global average production data directly collected and aggregated by IAI.

Energy inputs were modeled to reflect the fuel and electricity productions of specific countries where mining activities occurred. In the case of direct bauxite imports to North America, the energy profile is modeled based on the weights shared by each source countries as shown in **Figure 10**.

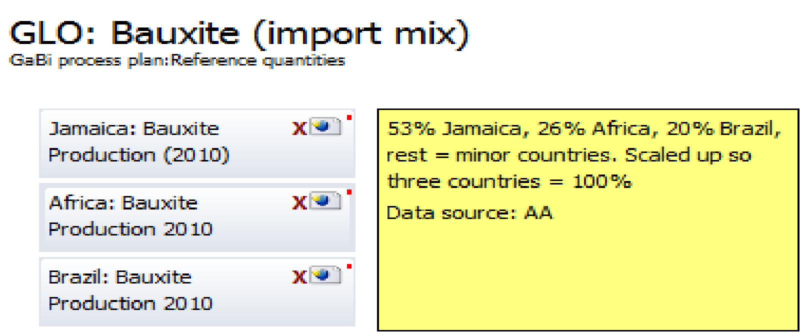

Figure 10: Bauxite imports into North America.

An illustration of the bauxite mining model is shown in **Figure 11**.

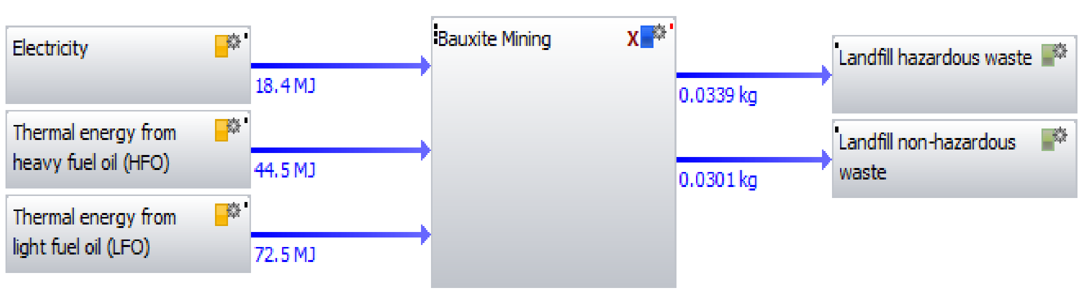

Figure 11: Bauxite mining model. Flows are representative for the production of 1000 kg of bauxite.

5.1.1.1.4 Unit Process Inputs and Outputs

Unit process inputs and outputs of bauxite mining are shown in **Table 6.**

Table 6: Inputs and outputs for the bauxite mining process, flows are representative for 1000 kg bauxite production

Flow	Unit	Amount
Inputs		
Major Materials		
Bauxite Ore [Non renewable resources]	kg	1000.07
Water		
Water (surface) [Operating materials]	kg	502
Water (sea water) [Operating materials]	kg	660
Energy and Fuels		
Light Fuel Oil [Net calorific value]	MJ	72.5
Heavy Fuel Oil [Net calorific value]	MJ	44.5
Power [Electric power]	kWh	0.92
Outputs		
Products		
Bauxite [Inorganic intermediate products]	kg	1000
Waste for Disposal		
Overburden (deposited) [Stockpile dirt and rock]	kg	100
Hazardous waste (unspec.) [Hazardous waste]	kg	0.03392
Non-hazardous waste for land-filling [Waste for disposal]	kg	0.03008
Emissions to Water		
Waste water [Treated waste water release]	kg	50
Emissions for Air		
Dust (unspecified) [Particles to air]	kg	0.17
Water vapor [Inorganic emissions to air]	kg	450

5.1.1.2 Alumina Production

5.1.1.2.1 Unit Process Description

Alumina refining is a process of converting bauxite to aluminum oxide Al_2O_3 (alumina) using the Bayer process (e.g. Droy and Michaux 2003; Mylona et al. 2003; Frank et al. 2008). Most refineries use a mixture of blended bauxite to provide feedstock with consistent properties. The mixture is ground and blended with recycled plant liquor. This liquor contains dissolved sodium carbonate and sodium hydroxide recovered from previous extraction cycles plus supernatant liquor recycled from red mud holding ponds. The slurry is heated and pumped to digesters, which are heated in pressure tanks. In digestion, iron and silicon impurities form insoluble oxides called red mud. The red mud settles out and a rich concentration of sodium aluminates is filtered and seeded to form hydrate alumina crystals in precipitators. These crystals are then heated in a calcination process. The heat in the calciners drives off combined water leaving alumina deposited.

This step of manufacturing begins with the processing of beneficiated bauxite and ends with the output of alumina to be subsequently processed in the smelters in North America. The operations associated with this unit process include (AA, 1998; IAI, 2013):

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

5.1.1.2.2 Source of Raw Material and Energy

Raw materials for alumina production include bauxite, caustic soda, sodium carbonate, etc. As it is mentioned in section 5.1.1.1.2, almost all bauxite is imported and the source countries are also listed. Caustic soda and sodium carbonate are either domestically produced or imported.

Source of energy for alumina production and transportation is correspondent with the countries where production activities occur.

5.1.1.2.3 Unit Process Model

According to the IAI survey, the production of 1 metric ton of alumina requires approximately 2.881 metric tons of bauxite (taking into account the purity of bauxite and losses during processing and transportation) (IAI, 2013). This is a representative global average that has been adopted to model both the domestic and the imported part of the alumina productions for North America.

Metallurgical alumina consumption was estimated to be approximately 9.1 million metric tons in North America in 2010. According to the USGS, domestic alumina production was 4,871,000 metric tons in the region (USGS, 2011). Apparently, the rest of alumina demand was met through imports. The fraction of alumina imports to total metallic alumina consumption was approximately 46% (**Figure 9**).

As with the bauxite mining process case, it was assumed that the source of alumina imports to the United States is representative of the entire North American region since the information for Canada is not available. Such assumption would have minor effect on the total environmental footprint and would significantly simplify the overall model adopted for alumina refining and thereby reduce possible errors and uncertainties.

The imports of alumina from Australia, Suriname and Brazil accounted for approximately 75% of the total alumina imports to the U.S. The country-specific breakdown of alumina imports to the U.S. in 2010 is given in **Table 7**.

Table 7: Source of alumina imports to the U.S. in 2010 [USGS, 2011]

Country	Alumina imports (1000 metric tons)
Australia	572
Brazil	233
Canada	62
France	23
Germany	81
Jamaica	84
Suriname	488
Venezuela	56
Others	120
Total	**1,720**

The alumina model is composed of two streams of production activities – domestic and import. All material and energy inputs as well as product outputs are scaled down to represent the production of one metric ton of alumina. An illustration of the alumina production process is shown in **Figure 12**.

The transportation of raw material, bauxite, from the mining countries to North America is considered in the model to create a bauxite import mix model as shown in **Figure 10**. It is assumed that bauxite is transported through bulk commodity ocean carriers utilizing heavy fuel oil as its energy source. The transportation distance was approximated based upon the average nautical distance between a major port in each of the bauxite exporting countries and New Orleans in the U.S. or Port Cartier in Canada. The transportation distance for bauxite imports from “Other” countries was based upon the weighted average distance from the countries comprising the “Others” category. The transportation distance was estimated using a web-based calculator (PortWorld Distances, 2012).

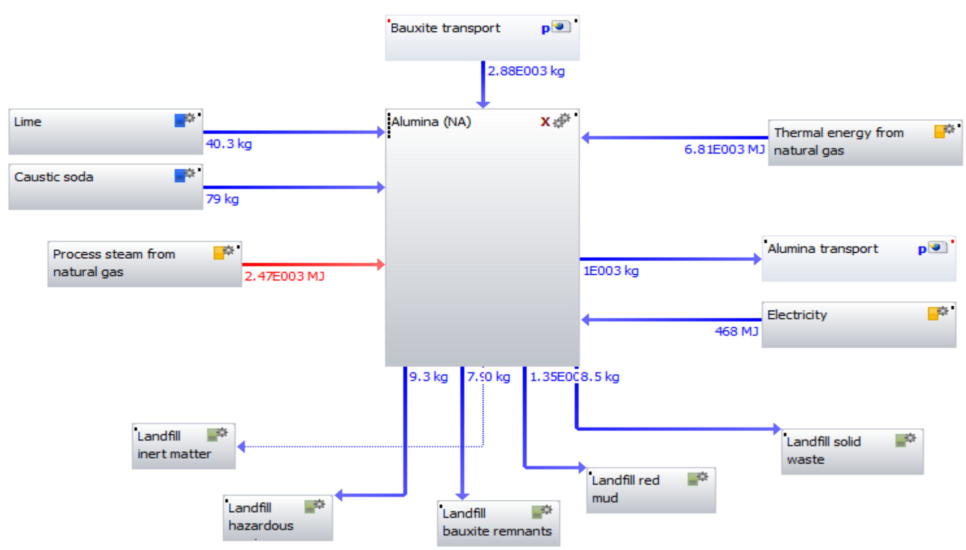

Figure 12: Alumina (Al2O3) production process in the North America in 2010. Flow quantities are representative of 1000 kg of alumina production.

5.1.1.2.4 Unit Process Inputs and Outputs

The unit process inputs and outputs are listed in **Table 8**, with the share of domestic production of 53.6 percent and imports of 46.4 percent.

Table 8: Inputs and outputs for the alumina production unit process, flows are representative for 1000 kg alumina production, with domestic production of 53.6 percent and imports of 46.4 percent.

Flows	Unit	Amount
Inputs		
Major Materials		
Bauxite	kg	2881
Auxiliary Materials		
Sodium hydroxide (caustic soda) [Operation materials]	kg	78.96
Quicklime [Operation materials]	kg	40.3
Water		
Sea water	kg	565
Surface water	kg	2571
Energy and Fuels		
Coal [Net calorific value]	MJ	805.5
Light fuel oil [Net calorific value]	MJ	1.64
Power [Electric power]	kWh	106.2
Heavy fuel oil [Net calorific value]	MJ	1771.6
Steam [Net calorific value]	MJ	1326
Natural gas [Net calorific value]	MJ	6100.4
Outputs		
Products		
Aluminum oxide (alumina)	kg	1000
Waste for recovery		
Bauxite Residue	kg	2.3
Other	kg	5.6
Waste for disposal		
Red mud (dry) [Waste for disposal]	kg	1354
Waste (non-hazardous)	kg	8.5
Waste (hazardous)	kg	9.28
Emissions to air		
Particulates	kg	0.56
SO_2	kg	2.4
NOx (as of NO_2)	kg	0.68
Mercury (+II) [Heavy metals to air]	kg	0.0002
Water vapour [Inorganic emissions to air]	kg	1200
Emissions to water		

Suspended solids	kg	0.015
Oil and grease	kg	0.767
Mercury (+II) [Heavy metals to fresh water]	kg	7.0E-08
Water (treated waste water release to surface water)	kg	1360

5.1.1.3 Anode Production

5.1.1.3.1 Unit Process Description

Anode is a consumable operating material used for primary aluminum production during an electrolysis process. Anode is made of carbon and is suspended on steel rods in the electrolysis cells, also called reduction cells. As the electric current flows through the electrolyte, a molten mixture of cryolite ($Na3AlF6$) and alumina, it breaks down the dissolved alumina into its component elements as metallic aluminum and oxygen gas. The oxygen reacts with the carbon anodes forming into CO and $CO2$ gases (Altenpohl, 1998).

There are two generic types of reduction cells: prebake and Söderberg (Anseen, Okstad, Innvar, & Olsen, 1979; Bergsdal, Strömann, & Hertwich, 2004; IAI, 2013). The Söderberg design has a single anode which covers most of the top surface of the 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 has pre-fired blocks of solid carbon suspended from axial busbars. The busbars both hold the anodes in place and carry the current required for electrolysis.

The process for making anodes for both technologies, e.g., the anode paste for Söderberg technology or prebaked blocks for prebake technology, is identical. Petroleum coke is calcined, ground and blended with coal pitch to form a paste that is subsequently extruded into blocks or briquettes and allowed to be cooled. While the briquettes are sent directly to the pots for consumption, the blocks are then sent to a separate baking furnace to be baked.

Baking furnace technology has evolved from simple pits that discharge volatiles to the atmosphere during the baking cycle to closed loop type designs that convert the caloric heat of the volatile into a process fuel that reduces net energy consumption.

In North America, approximately 95 percent of primary aluminum production in 2010 was from prebake facilities and the remaining 5 percent from Söderberg facilities.

The operations associated with anode production include (AA, 1998; IAI, 2013):

- recovery of spent anode materials,
- anode mix preparation, 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 primary aluminum smelter.

5.1.1.3.2 Source of Raw Material and Energy

In North America, anodes are either produced domestically or imported from overseas. Raw materials for anode production are normally locally sourced, so does energy for the productions. Due to the minimal effect on the overall footprint of anode production by variations in the source of raw material and energy from different countries, a global average profile is used to represent both the domestic productions and imports for anode consumed in North America.

5.1.1.3.3 Unit Process Inputs and Outputs

The unit process inputs and outputs are listed in **Table 9** and **Table 10**, for both anode production (Prebake Technology) and anode paste production (Söderberg Technology), respectively.

Table 9: Inputs and outputs for the anode production (Prebake Technology) unit process, flows are representative for the production of 1000 kg of anode.

Flow	Unit	Amount
Inputs		
Materials		
Petrol coke (C carrier)	kg	667.0
Hard coal pitch (C carrier)	kg	148.0
Recycled anode butts (carbon carrier)	kg	214.4
Refractory [Minerals]	kg	7.3
Steel [Metal parts]	kg	6.2
Cooling water	kg	1100
Energy and Fuels		
Power [Electric power]	kWh	124.2
Thermal energy from light fuel oil	MJ	256.7
Thermal energy from heavy fuel oil	MJ	1413.5
Thermal energy from natural gas	MJ	1915.1
Outputs		
Products		
Anode (C carrier)	kg	1000
By-Product for External Recycling		
Refractory	kg	4.8
Steel	kg	1.92
Carbon waste for recovery	kg	17.1

Emissions to air		
Particulates	kg	0.239
SO_2	kg	3.05
NOx (as NO_2)	kg	0.56
Gaseous fluorides (as F)	kg	0.0077
Particulate fluorides (as F)	kg	0.0022
Benzo{a}pyrene [BaP]	kg	0.00022
Total polycyclic aromatic hydrocarbons [Group PAH to air]	kg	0.051
Emissions to Water		
Treated waste water release	kg	990
Oil (unspecified) [Hydrocarbons to fresh water]	kg	0.0078
Polycyclic aromatic hydrocarbons [Hydrocarbons to fresh water]	kg	0.00001
Solids (suspended) [Particles to fresh water]	kg	0.034
Solid Waste for Disposal		
Scrubber sludge	kg	0.35
Refractory	kg	2.4
Other non-hazardous waste	kg	1.3
Other hazardous waste	kg	2.8

Table 10: Inputs and outputs for anode paste production (Söderberg Technology) unit process, flows are representative for the production of 1000 kg of anode paste.

Flow	Unit	Amount
Inputs		
Materials		
Coke (C carrier)	kg	708.89
Hard coal pitch (C carrier)	kg	298.51
Cooling water	kg	1290
Energy and Fuels		
Power [Electric power]	kWh	46.78
Thermal energy from light fuel oil	MJ	19.7
Thermal energy from heavy fuel oil	MJ	309.6
Thermal energy from natural gas	MJ	53.6
Outputs		
Products		
Anode paste (C carrier)	kg	1000
By-Product for External Recycling		
Carbon waste for recovery	kg	6.6
Emissions to air		
Particulates	kg	0.1
SO_2	kg	9.7
NOx (as NO_2)	kg	1.51

Benzo{a}pyrene [BaP]	kg	0.000012
Total polycyclic aromatic hydrocarbons [Group PAH to air]	kg	0.0075
Emissions to Water		
Treated waste water release	kg	1090
Polycyclic aromatic hydrocarbons [Hydrocarbons to fresh water]	kg	0.00021
Solids (suspended) [Particles to fresh water]	kg	0.01
Solid Waste for Disposal		
Other solid waste	kg	1.5

5.1.1.4 Aluminum Smelting – Electrolysis

5.1.1.4.1 Unit Process Description

Molten aluminum is produced from alumina by the Hall-Heroult electrolytic process (e.g. Frank, et al., 2008; Grjotheim & Kvande, 1993). This involves two steps: dissolving the alumina (Al_2O_3) produced in the preceding alumina refining step in a molten cryolitic bath, and passing electric current through this solution, thereby decomposing the alumina into aluminum and oxygen. Aluminum is tapped out of the reduction cell (pot) at daily intervals and the oxygen bonds with the anode carbon to form carbon dioxide and carbon monoxide.

As stated in the previous process, there are two generic types of electrolysis technologies: Prebake and Söderberg. The two technologies are differentiated by the type of anodes they consume. As a consequence of advanced design and better computer control of the Prebake technology, the efficiency and emission levels have been significantly improved. Approximately 95 percent of the production in North America in 2010 was from Prebake technology and 5 percent was from Söderberg technology.

Aluminum smelters typically use air pollution control systems to monitor and 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 re-circulate an alkaline solution to absorb emissions. Unlike dry scrubbers, wet scrubbers absorb carbon dioxide, nitrogen oxide and sulfur dioxide that are entrained in the waste water liquor.

This unit process begins with the processing of alumina and ends with the output of molten aluminum to be subsequently cast into primary ingot in the casting process. The operations associated with electrolysis include (AA, 1998; IAI, 2013):

- recovery, preparation, and handling of process materials,
- manufacture of major process equipment (e.g., cathode shells),
- process control activities (metal, bath, heat),
- maintenance and repair of plant and equipment, and
- treatment of process air, liquids, and solids.

5.1.1.4.2 Source of Raw Material

Major raw material of this unit process is alumina and auxiliary materials include carbon anode, aluminum fluoride, and other minor materials.

As described in the previous unit process, about 54 percent of alumina consumed in North America in 2010 was produced domestically and the rest of it was imported. Carbon anodes were also partially domestic production and partially import. Other auxiliary materials were either imported or domestically produced but the quantities of consumption of those materials were minor.

5.1.1.4.3 Source of Energy – The Electrical Power Mix

Electricity is the primary energy source of the electrolysis process. Electricity serves in this case both as energy and “raw material”, of which electrons are participated in the electrochemical reactions:

- The net reduction reaction: $2Al_2O_3 + 3C \Leftrightarrow 4Al + 3CO_2$
- Anode reactions: $Al_2O_2F_6^{2-} + 2F^- + C \rightarrow CO_2 + 2AlF_4^- + 4e^-$, and
  $Al_2O_2F_4^{2-} + 4F^- + C \rightarrow CO_2 + 2AlF_4^- + 4e^-$
- Cathode reactions: $AlF_6^{3-} + 3e^- \rightarrow Al + 6F^-$ and $AlF_4^{3-} + 3e^- \rightarrow Al + 4F^-$

The electricity input during electrolysis is a critical LCI parameter that can significantly influence the environmental footprint of the overall primary aluminum production process. Accurately modeling of electrical power consumption is therefore a significant step toward accurate documentation of the life cycle inventory. Based on the principles of ISO 14040 series, the best approach is to track the exact actual source of power generation and the corresponding quantities of consumptions at the production facilities covered by this study.

Unlike most other manufacturing industries where the electrical power usually comes from a general grid of which the electricity is generated from a mixture of sources, all primary aluminum smelting companies in North America get their electricity either through purchasing power directly from specific power generators or through building and owning their own power generation facilities. And the smelting facility itself is usually located not far from the power generation facility. Consequently, the aluminum industry is unique in its ability to identify the specific source of power generation, e.g., its exact energy footprint. And the industry has been working rigorously during the past 50 years to select cleaner electrical power to improve its overall environmental footprints.

Based on the IAI annual energy survey which covers all aluminum smelting facilities in North America, the 2010 production year power mix is shown in **Table 11**:

Table 11 : Electrical power mix of North America primary aluminum production in 2010. The statistical total of primary ingot output was 4,690,000 metric tons in 2010 and the reported total was 4,439,931 metric tons. Source: IAI.

Power Source	North America	NA Share of Power Source	Power Intensity (kWh/1000 kg Al)
Hydro (GWh)	50,355	75.1%	11,341
Coal (GWh)	16,095	24.0%	3,625
Oil (GWh)	7	0.0%	2
Natural gas (GWh)	316	0.5%	71
Nuclear (GWh)	320	0.5%	72
Power total (GWh)	67,093	100.0%	15,111

5.1.1.4.4 Domestic Primary Aluminum Consumption Mix

The majority of North American domestic primary aluminum consumption comes from domestic production during the past decade. There is a small amount of imported metal each year. At the same time, there is also metal export. The traditional major sources of countries of metal imports are Russia, Brazil, Argentina, Venezuela, and the United Arab Emirates.

As is shown in **Table 12**, the North American primary aluminum industry ended up in 2010 as a net primary metal exporter. Also shown in **Table 13** are the top five primary aluminum exporters to North America in 2010, totalling more than 70 percent of the total exports to the region.

Table 12: Primary aluminum production and trade in North America in 2010, in Metric Tons

Category	Amount
Domestic (NA) Production	4,690,468
Total Import	851,646
Total Export	920,757
Net Export	69,111

Table 13: Top primary aluminum exporters to North America in 2010, in Metric Tons.

Country/Region	Amount
Russia	203,000
Argentina	138,000
Venezuela	123,000
United Arab Emirates	81,700
Brazil	57,300

5.1.1.4.5 Unit Process Model

The unit process model is developed by taking into considerations of all of the above. The model adopts the global average quantities of material inputs with specific sourcing of the materials by the North American primary aluminum industry. The energy input part of the model is constructed with specific North American profile regarding to quantities and sources, of which the information was directly obtained from production facilities through the IAI survey.

Illustrations of the models for both Prebake technology and Soderberg technology are shown in **Figure 13** and **Figure 14**, respectively, with the power mix model separately showing in **Figure 15**. Note that the power mix for both countries is normalized through a weighted average exercise to comply with information disclosure regulations.

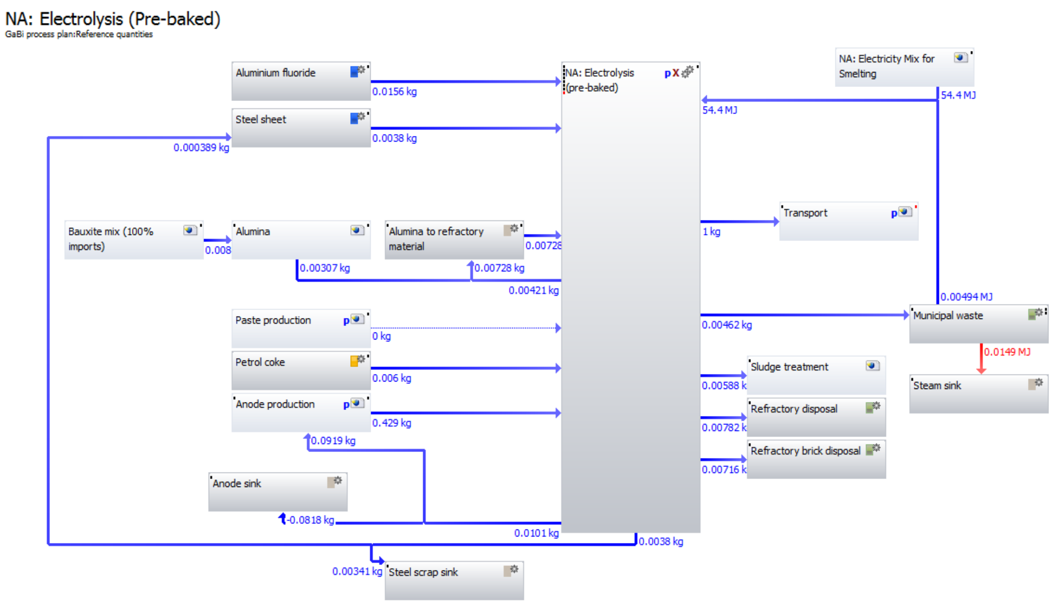

Figure 13: Electrolysis process model for crude aluminum production – *Prebake* technology, flows are representative for the production of 1000 kg of primary aluminum

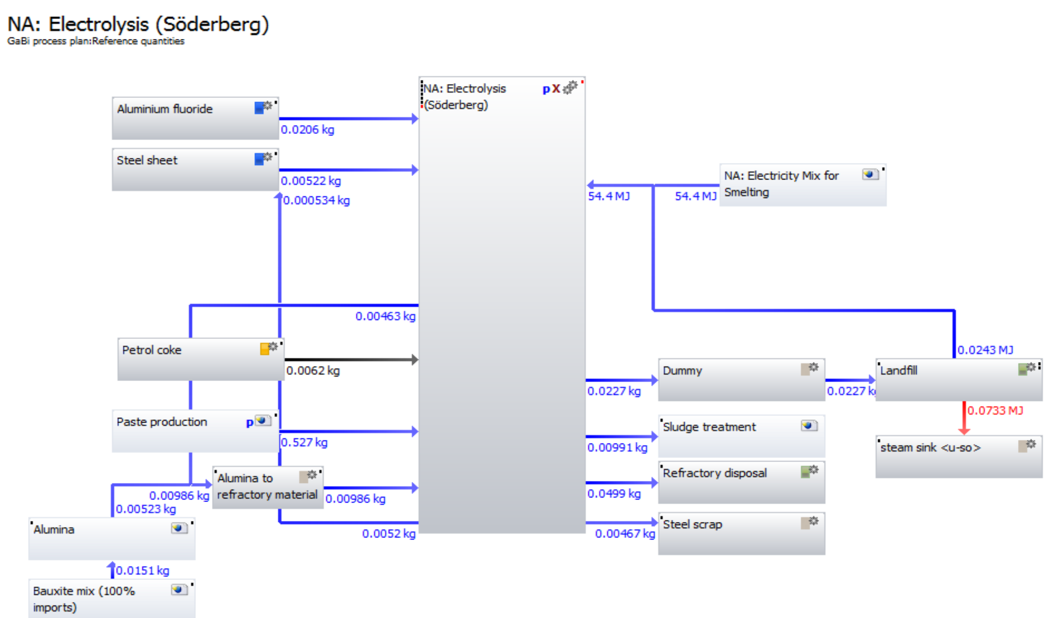

Figure 14: Electrolysis process model for crude aluminum production – *Soderberg* technology, flows are representative for the production of 1000 kg of primary aluminum

Figure 15: Electrical power mix for electrolysis. Flows are representative for production of 1000 kg of primary aluminum.

5.1.1.4.6 Unit Process Inputs and Outputs

The unit process inputs and outputs of both Prebake and Söderberg technologies are shown in **Table 14** and **Table 15**, respectively.

Please note that due to the very small proportion and the limited number of facilities involved in Söderberg technology productions, the electricity consumption is normalized for both technologies through a weighted average exercise to comply with relevant laws and regulations on information disclosure. The same treatment is done for the emissions of perfluorocarbon (PFC).

Table 14: Inputs and outputs for the electrolysis unit process – *Prebake* technology, flows are representative of the production of 1000 kg primary aluminum.

Flow	Unit	Amount
Inputs		
Materials		
Aluminum oxide (alumina)	kg	1935
Aluminum fluoride (Na_3AlF_6)	kg	15.6
Anode (C carrier)	kg	428.6
Refractory material	kg	7.3

Cathode	kg	6.0
Steel	kg	3.8
Fresh Cooling Water	kg	3890
Energy and fuels		
Power [Electric power]	kWh	15111
Outputs		
Products		
Aluminum (liquid metal)	kg	1000
Waste for recovery		
Aluminum oxide waste (alumina)	kg	4.2
Refractory (spent pot liner mix)	kg	7.2
Used anode	kg	10.1
Waste carbon mix	kg	4.6
Steel scrap	kg	3.8
Emissions to air		
Carbon dioxide (calculated based on anode consumption)	kg	1534
Particulates	kg	1.94
Particulate fluoride (as F)	kg	0.52
Gaseous fluoride (as F)	kg	0.50
Benzo{a}pyrene [Group BaP to air]	kg	0.00011
Polycyclic aromatic hydrocarbons [Group PAH to air]	kg	0.0088
Sulphur dioxide	kg	15.28
Nitrogen oxides	kg	0.26
Tetrafluoromethane (CF_4)	kg	0.0769
Hexafluoroethane (C_2F_6; R116)	kg	0.0106
Emissions to water		
Treated waste water release	kg	3650
Fluoride (as F)	kg	0.033
Oil (unspecified)	kg	0.0036
Solids (suspended)	kg	0.5
Polycyclic aromatic hydrocarbons (PAH, unspec.)	kg	7.30E-06
Waste for disposal		
Refractory (spent pot liner mix)	kg	7.8
Scrubber sludge	kg	5.88

Table 15: Inputs and outputs for the electrolysis unit process – *Söderberg* technology, flows are representative of the production of 1000 kg primary aluminum.

Flow	Unit	Amount
Inputs		
Materials		

Aluminum oxide (alumina)	kg	1923.76
Aluminum fluoride (Na_3AlF_6)	kg	20.6
Anode paste (C carrier)	kg	527
Refractory material	kg	9.86
Cathode	kg	6.2
Steel	kg	5.22
Fresh Cooling Water	kg	3890
Energy and fuels		
Power [Electric power]	kWh	15111
Outputs		
Products		
Aluminum (liquid metal)	kg	1000
Waste for recovery		
Aluminum oxide waste (alumina)	kg	4.63
Refractory (spent pot liner mix)	kg	32.1
Waste carbon mix	kg	22.7
Steel scrap	kg	5.22
Emissions to air		
Carbon dioxide (calculated based on anode consumption)	kg	1571.5
Particulates	kg	7.7
Fluoride (as F)	kg	0.78
Hydrogen fluoride (as F)	kg	1.19
Benzo{a}pyrene [Group BaP to air]	kg	0.006
Polycyclic aromatic hydrocarbons [Group PAH to air]	kg	0.43
Sulphur dioxide	kg	11.79
Nitrogen oxides	kg	0.16
Tetrafluoromethane (CF_4)	kg	0.0769
Hexafluoroethane (C_2F_6; R116)	kg	0.0106
Emissions to water		
Treated waste water release	kg	3650
Fluoride (as F)	kg	0.29
Oil (unspecified)	kg	0.017
Solids (suspended)	kg	0.67
Polycyclic aromatic hydrocarbons (PAH, unspec.)	kg	0.00243
Waste for disposal		
Refractory (spent pot liner mix)	kg	17.78
Scrubber sludge	kg	9.91

5.1.1.4.7 Perfluorocarbon (PFC) Emissions in Aluminum Smelting

PFC emissions (as Hexaflouroethane and Tetrafluoroethane gases) in the aluminum smelting process are listed in **Table 16**. It is a normalized quantity (weighted average) for both Prebake and Söderberg technologies across all facilities in North America. The emissions are normalized to comply with the relevant laws and regulations on information disclosure of both Canada and the United States. The numbers of facilities involved in Söderberg technologies are too small to disclose the information separately.

The CO_2 equivalents (100 years) of the emissions are calculated based on CML 2001[1] values of 5700 (kg) for CF_4 and 11900 (kg) for C_2F_6 .

Table 16: Perafluorocarbon (PFC) emissions of aluminum smelting in North America in 2010, representing 1000 kg of aluminum ingot.

Category	Unit	Amount
Tetrafluoroethane (CF_4) (CO_2 eq./ton aluminum ingot)	kg	438.33
Hexaflouroethane (C_2F_6) (CO_2 eq./ton aluminum ingot)	kg	126.14

5.1.1.5 Primary Ingot Casting (Cast House)

5.1.1.5.1 Unit Process Description

Molten metal siphoned from the pots is sent to a resident cast house found in each smelter. In some cases, due to proximity, molten metal is transported directly to a semi-fabrication facility. Molten metal is then transferred to a holding furnace where the composition is adjusted to the specific alloy requested by a customer. In some instances, depending on the application and 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 of carbon monoxide, argon, and chlorine through the metal. Fluxing may also be accomplished with an inline degassing technology which performs the same function in a specialized degassing unit.

Fluxing removes entrained gases and inorganic particulates by flotation to the surface of the metal. These impurities (typically called dross) are skimmed off. The skimming process also takes some aluminum and dross are normally further processed to recover the aluminum 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. Subsequently, metal is 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 aluminum coils.

[1] The USEPA and other governments are still using the IPCC 2nd Assessment values of 6,500 for CF4 and 9,200 for C2F6.

This unit process begins with the processing of molten primary aluminum and ends with the output of ingots suitable for rolling, extruding, or shape casting. The various operations carried out in the cast house include (AA, 1998; IAI, 2013):

- Pretreatment of hot metal (cleaning and auxiliary heating);
- Recovery and handling of internal process scrap;
- Batching, metal treatment, and casting operations;
- Homogenizing, sawing, and packaging and casting operations;
- Maintenance and repair of plant and equipment; and
- Treatment of process air, liquids, and solids.

5.1.1.5.2 Source of Raw Material and Energy

The source of raw material for cast house is the molten metal produced during the electrolysis (smelting) process. The cast house is usually located inside the facility of a smelter so the source of energy is the same as the electrolysis process.

Alloying materials are also added during ingot casting. However, these materials will be substituted by the same amount of aluminum elements in the model for simplicity and other considerations. The rationality of such substitution will be explained in the next section.

5.1.1.5.3 Unit Process Model

The model for the primary ingot casting process is illustrated in **Figure 16**. Alloying materials are not considered in the model. In stead, all alloying elements are substituted by the same quantities of aluminum for the purpose metal balancing.

There are three major considerations for such substitution. The first consideration is that there is a great variety of alloyed aluminum ingots produced in the cast house and the alloying elements are all slightly different depending on the end-use of the ingots. The second consideration is that the proportion of alloying elements is very small in most cases, usually smaller that 5 percent, and that some of the alloying elements and their exact quantities are proprietary information of individual producers and they are mostly protected by patents. The third consideration is that substituting alloy materials with primary aluminum does not end up with under-counting of the life cycle inventories since the approach of substitution used here is fairly conservative.

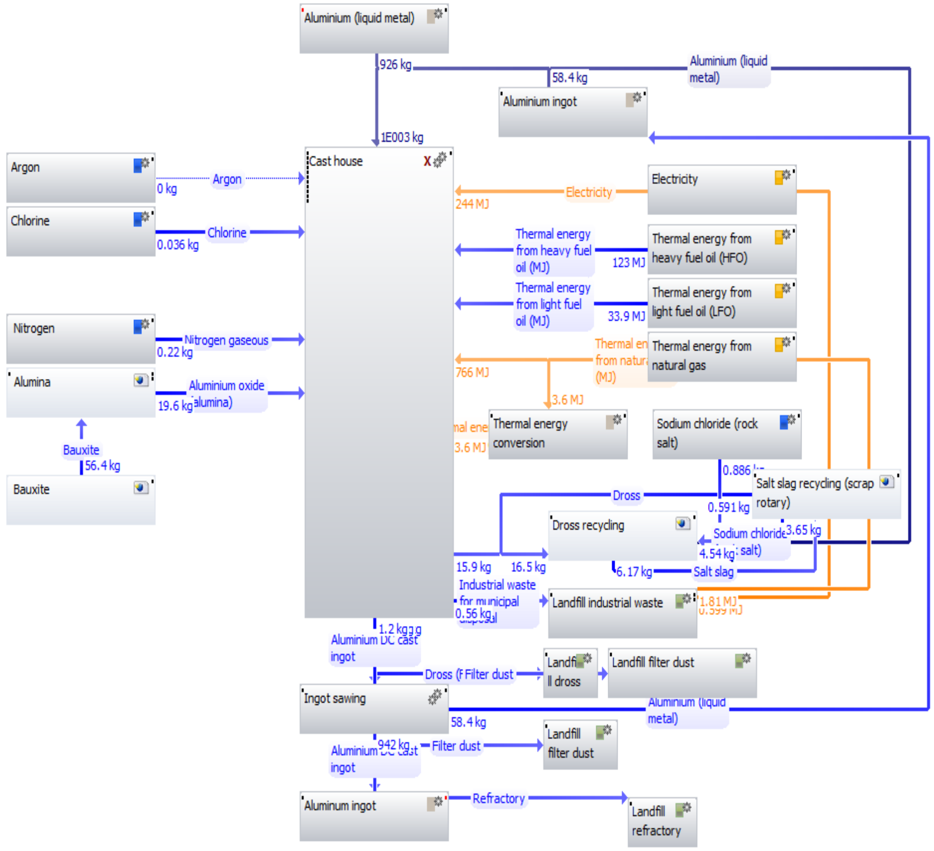

Figure 16: Primary ingot casting process model for primary aluminum production. Flows are representative for 1000 kg of primary aluminum production.

5.1.1.5.4 Unit Process Inputs and Outputs

The unit process inputs and outputs are shown in **Table 17**.

Table 17: Inputs and outputs for primary ingot casting unit process. Flows are representative for the production of 1000 kg of primary aluminum.

Flow	Unit	Amount
Inputs		
Materials		
Molten aluminum (liquid metal)	kg	1000
Alloy components (substituted with aluminum)	kg	19.57
Chlorine	kg	0.036
Nitrogen gas	kg	0.22
Fresh cooling water	kg	3490
Energy and fuels		
Power [Electric power]	kWh	67.65
Thermal energy from light fuel oil	MJ	33.92
Thermal energy from heavy fuel oil	MJ	122.86

Thermal energy from natural gas	MJ	766.04
Thermal energy from propane	MJ	3.6
Outputs		
Products		
Aluminum cast ingot	kg	1000
Waste for recovery		
Dross	kg	21.15
Filter dust	kg	1.49
Waste for disposal		
Filter dust	kg	0.46
Other industrial waste (solid)	kg	0.56
Refractory	kg	1.2
Emissions to air		
Particulates	kg	0.037
Hydrogen chloride	kg	0.024
Nitrogen oxide	kg	0.072
Sulphur dioxide	kg	0.11
Emissions to water		
Treated waste water release	kg	3260
Oil (unspecified)	kg	0.037
Solids (suspended)	kg	0.14

5.1.2 LCI Results of Primary Aluminum Ingots

In this section, the most important LCI results of primary aluminum production are presented for the production of 1 metric ton of aluminum ingot in the North America region. The model used to calculate the LCI was shown previously in **Figure 9**. The results of the LCI are shown in**Table 18**. The breakdown of inventories for energy and carbon dioxide emissions is shown in **Table 19**. Explanation and analysis of the two particular parameters are shown in the subsections followed.

Table 18: Selected LCI parameters for the production of 1000 kg of primary aluminum ingot in North America.

Inventory Category	Amount
Energy (MJ)	
Non-renewable energy	8.83E+04
Hydroelectric energy	4.92E+04
Other renewable energy (except for hydro)	6.71E+02
Resources (kg)	
Bauxite	6.19E+03
Net Process Water (Excluding Energy & Ancillary Material)	5.38E+03
Air Emissions (kg)	
Carbon dioxide	7.87E+03
Carbon monoxide	3.60E+00
Chlorine	4.81E-04
Flourine/Fluorides	5.49E-01
Hydrogen chloride	4.78E-01
Hydrogen fluoride	6.08E-01
Nitrogen oxides	1.78E+01
Nitrous oxide	9.99E-02
Sulphur oxides	4.24E+01
Non-methane VOCs	1.20E+00
Methane	1.33E+01
Dust (PM10)	1.80E-04
Dust (PM2.5)	1.42E+00
Water Emissions (kg)	
Biological oxygen demand (BOD)	2.54E-02
Chemical oxygen demand (COD)	1.26E+00
Heavy metals	6.64E+01
Ammonia	2.34E-03
Flourine/Flourides	1.49E+00
Phosphate	1.58E-03
Solid Waste (kg)	
Total waste (excluding mining overburden)	3316.842

Table 19: Primary energy and CO_2 emissions breakdown by unit process for the production of 1000 kg of primary aluminum ingot in North America

Inventory parameter	Unit	Bauxite mining	Alumina Refining	Electrolysis	Cast house	Total
Primary Energy Demand	GJ/ton	1.04	30.78	104.24	2.04	138.1
Non renewable	GJ/ton	0.98	15.21	55.24	1.98	73.41
Renewable	GJ/ton	0.06	0.41	49.00	0.06	49.53
CO_2 emissions	ton CO_2/ ton	0.07	2.01	5.67	0.12	7.875

5.1.2.1 Primary Energy Demand

The primary energy demand (PED) is a measure of the total amount of primary energy extracted from the earth, including both non-renewable (i.e. fossil fuels and nuclear) and renewable (hydropower, wind, solar, etc.) resources, taking into account the energy needed for extractions and fuel conversions, the efficiency of electric power generation and heating methods, as well as transmission and distribution losses.

It is essential for non-LCA practitioners and non-technical professionals to understand the fundamental difference between the term **energy consumption** for daily life and the term **Primary Energy Demand** in LCA. Energy consumption usually refers to the amount of calorific value used by consumers and the quantity is measured through a meter on the **usable format** of the energy itself, such as electricity, gasoline or natural gas. Energy demand, however, refers to a much larger scope and it is the amount of total energy that a product or activity is **RESPONSIBLE** for being consumed, and it is measured in **Primary Energy** format – tracking all the way back to the resource extraction point. For instance, the PED of primary aluminum ingot refers to not only all the energy related to production activities of the production processes, but also the energy that is associated with the production of other materials used in the aluminum production processes, such as caustic soda, aluminum fluorides, quicklime, various gases, steel, packaging, etc.

The energy efficiency coefficient indicates the efficiency of the energy conversion (and its transmission and distribution, if applicable) system, and relates the primary energy demand and secondary energy through the following equation:

$$\text{Primary Energy Demand } (1) \times \text{Conversion efficiency} = \text{End energy}(2)$$

The breakdown of primary energy demand by unit processes is illustrated in **Figure 17**, including non-renewable and renewable resources. The production of 1 metric ton of primary aluminum ingot representative for North American conditions requires 73.4 GJ of energy from non-renewable sources and 49.5 GJ from renewable sources. The electrolysis process accounts for **75 percent** of the total primary energy demand. The electrolysis and the anode production (anode production contributes approximately 14 percent of the primary energy demand for electrolysis) are highly energy intensive processes compared to other unit processes.

It is worthwhile to note that the major energy input during the electrolysis process is electricity and **75 percent** of the electricity is from renewable hydropower. However, as a result of the different power generation efficiencies, the overall non-renewable fraction of primary energy for electrolysis is still greater than the renewable fraction. Renewable energy is **36 percent** of the total energy demand and non-renewable energy is **64 percent**.

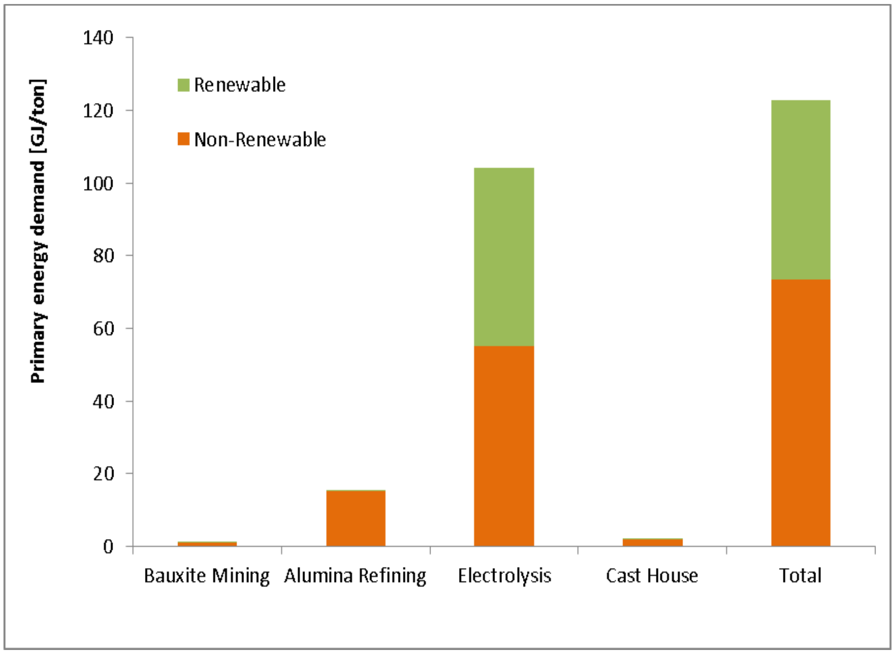

Figure 17: Primary energy demand from renewable and non-renewable sources for primary aluminum ingot production per unit process and in total. Electrolysis accounts for the largest primary energy demand (75 percent).

5.1.2.2 Carbon Dioxide Emissions

Carbon dioxide is one of the greenhouse gases that contributes to the global warming phenomenon. Carbon dioxide emissions are mainly associated with the conversion of fossil energy carriers (e.g. lignite, crude oil, natural gas) into thermal and/or mechanical energy by means of burning and are expressed in kilograms of CO_2. The breakdown of the carbon dioxide emissions is illustrated in **Figure 18**. It is calculated that 7.88 metric tons of carbon dioxide is associated with per metric ton of primary aluminum ingot produced. The carbon dioxide results are closely linked to the primary energy demand results and their graphs have much the same shape. The electrolysis process is the largest contributor, producing 5.67 metric tons of carbon dioxide for each ton of primary aluminum ingot produced. **The upstream emissions associated with the electricity supply chain account for 70 percent of the total 5.67 metric tons CO_2 for electrolysis**. The **overall share of the electrolysis process is 72 percent**.

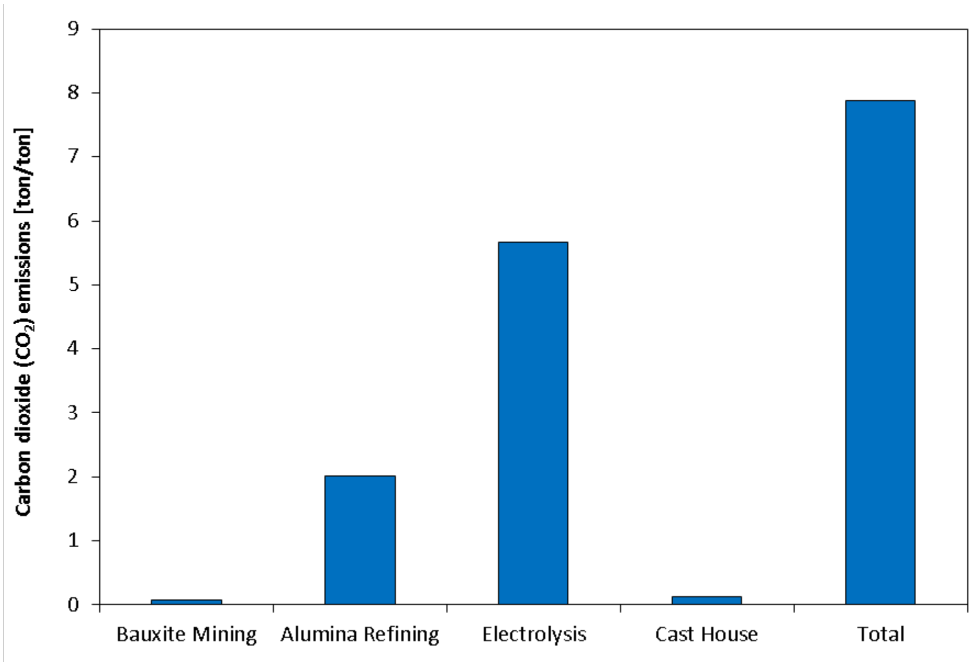

Figure 18: Carbon dioxide emissions associated with primary aluminum ingot production per unit process and in total. Electrolysis is the major contributor to the total CO_2 emissions and 70 percent is from the electricity supply chain.

5.1.3 LCIA Results

In this section, the Life Cycle Impact Assessment (LCIA) results are presented for the production of 1 metric ton of primary aluminum ingot in North America. Unlike the Life Cycle Inventory, which only reports sums for individual emissions, the LCIA includes methodologies for weighting and combining different emissions into a metric for the **potential impacts** of significant LCI.

As described in Section 4.2 of this report, the impact assessment results were calculated using characterization factors of TRACI 2.1 published by the US EPA.

The results of LCIA are shown in **Table 20**. Explanation and analysis on each of the impact categories are shown in the subsections followed.

Table 20: LCIA results for production of 1000 kg of primary aluminum ingot in North America.

Impact Assessment Category	Unit	Bauxite mining	Alumina Refining	Electrolysis	Cast house	Total
Primary Energy Demand	GJ/ton	1.04	30.78	104.24	2.04	138.1
Global Warming Potential	ton CO_2-eq/ton	0.078	2.219	6.512	0.128	8.937
Acidification Potential	kg SO_2-eq/ton	0.4	15.2	40.2	0.6	56.4
Eutrophication Potential	kg N-eq/ton	0.009	0.419	0.526	0.015	0.970
Smog Formation Potential	kg O_3-eq /ton	4	188	247	6	446

5.1.3.1 Acidification Potential

The acidification potential is a measure of emissions that cause acidifying effects to the environment and is expressed as kilogram SO_2 Equivalent.

The major acidifying emissions are nitrogen oxides (NO_x) and sulfur dioxide (SO_2), as well as ammonia emissions that lead to ammonium deposition. The acidification potential related to 1000 kg of primary aluminum ingot production in North America amounts to 56.4 kg SO_2 equivalent (**Figure 19**; **Table 20**).

The relative share of this acidification potential indicator from SO_2 emissions to air is 75 percent, and from NO_x emissions to air is 22 percent, with the remainder from hydrogen fluoride (2%), hydrogen chloride (<1%), and other trace emissions.

Breaking the emissions down by production stages shows that the **electrolysis process** is responsible for **71 percent** of the total acidification potential result; followed by **alumina refining** which has a **27 percent** contribution.

We also note that **74 percent** of the acidification impacts are associated with upstream emissions during **electricity production**.

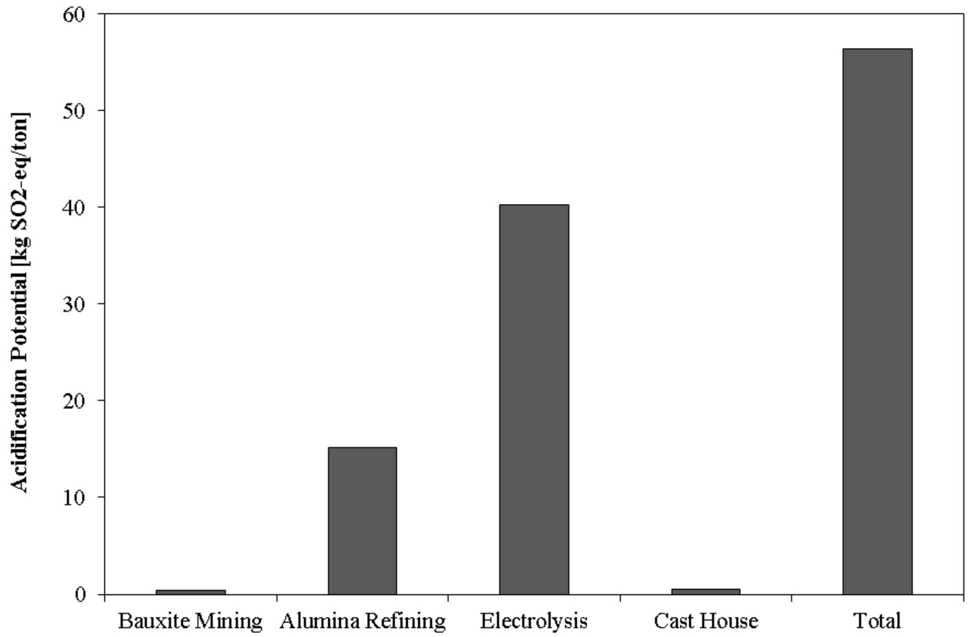

Figure 19: Acidification potential results for primary aluminum ingot production. 71 percent of the total acidification potential result is attributed to the process of electrolysis and upstream emissions from electricity generation account for 74 percent of the total AP.

5.1.3.2 Eutrophication Potential

The eutrophication potential is a measure of emissions that cause eutrophying effects to the environment and is expressed as kilogram of Nitrogen Equivalent. The eutrophication of aquatic systems is primarily caused by excessive inputs of nitrogen and phosphorus (mostly as a result of over-fertilization).

The eutrophication potential related to the manufacture of 1 metric ton of primary aluminum ingot in North America amounts to 0.97 kg Nitrogen equivalent (**Figure 20**; **Table 20**). The eutrophication potential from emissions to air (mainly NO_x emissions) contributes to 86 percent of the total impacts. The remaining 14 percent of the eutrophication potential is due to emissions to water (mainly from nitrate emissions, chemical oxygen demand COD and NO_x releases to water).

Breaking the impact down by contributions from different production stages, **Figure 20** shows that the **alumina refining and electrolysis processes** together are responsible for **97 percent** of the eutrophication impacts result, with individual contributions of 43 percent and 54 percent, respectively. Emissions to air from upstream processes (such as **electricity production**) account for approximately two-thirds (**67 percent**) of the total eutrophication potential result.

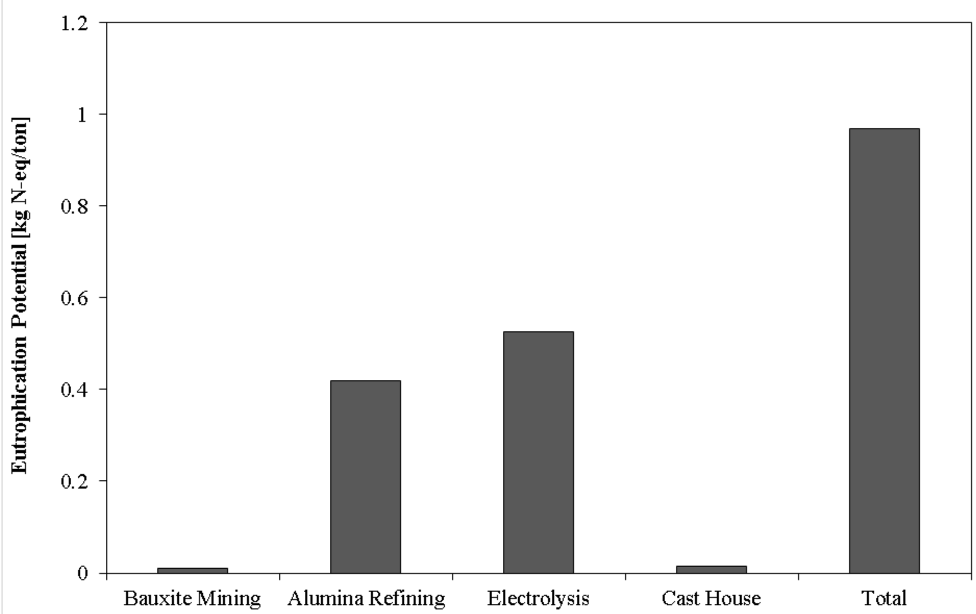

Figure 20: Eutrophication potential results for primary aluminum production. Alumina production and electrolysis together account for about 97 percent of the total EP of which indirect emissions to air account for 67 percent.

5.1.3.3 Global Warming Potential (100 Years)

The Global Warming Potential (GWP) is a measure of the emission of greenhouse gases (GHG) such as CO_2, perfluorocarbon (PFC), and methane (CH_4), and is expressed as kilogram of CO_2-equivalents. Greenhouse gas emissions are found to cause an increase in the absorption of radiation emitted by the sun and reflected by the earth, magnifying the natural greenhouse effect.

The total global warming potential (GWP) related to the production of 1 metric ton of primary aluminum ingot in North America is 8937 kg CO_2 equivalent.

A breakdown of the GWP impact by component greenhouse gases shows that almost 88 percent of the net GWP comes from CO_2, 6 percent from Tetrafluoromethane (CF_4), 4 percent from CH_4, 1 percent from Hexafluoroethane (C_2F_6), and less than 1 percent from nitrous oxide (N_2O).

A breakdown of the results by individual production stages is shown in **Figure 21** and it shows that **73 percent** of the global warming impacts come from the **electrolysis process**. **Alumina refining** is next largest contributor with a **25 percent** share of net global warming potential.

The share of global warming potential from direct greenhouse gas emissions is approximately **42 percent** of net GWP impact, while indirect CO_2 emissions (mainly from electricity production) account for another **58 percent** of net GWP impact.

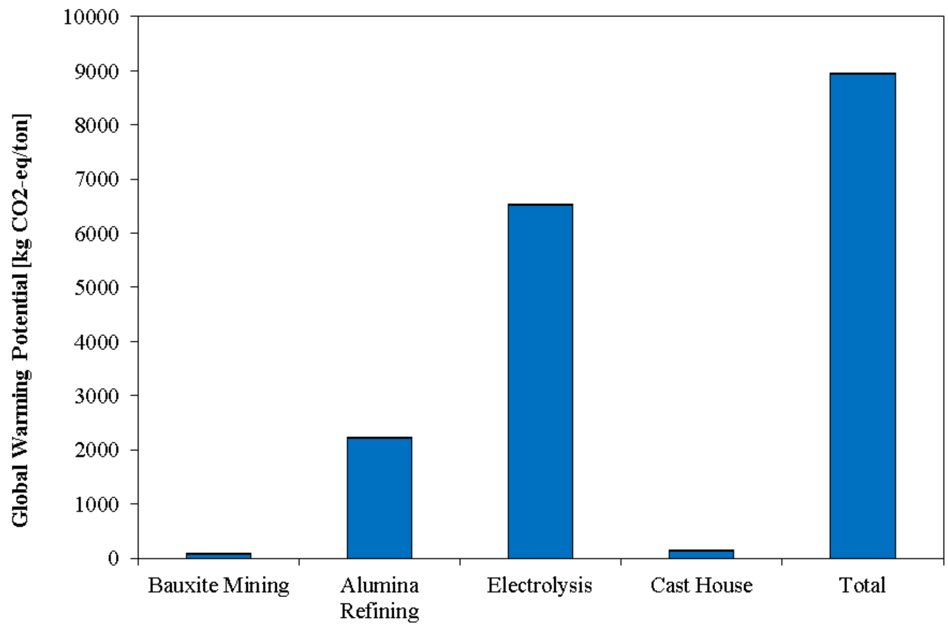

Figure 21: Global warming potential results for primary aluminum ingot production. The electrolysis process is responsible for 73 percent of the global warming impacts, of which 88 percent are due to CO_2 emissions.

GHG analysis and breakdown into scope 1, 2 and 3

It is worth to look further into the details of greenhouse gas emissions to identify hotspots as well as to assess the "liability" of emissions from different entities along the life cycle chain of products. Such understanding would be useful for policy and strategic planning purposes. For this consideration, the GHG emission results for the primary aluminum ingot production were further categorized applying the concept of scopes as outlined in the Greenhouse Gas (GHG) Protocol (WRI and WBCSD, 2004). As the GHG Protocol was not designed to be applied to products[2], the results categorization was performed as closely as possible to the requirements of the GHG Protocol. Following the concept of scopes, the breakdown of the GHG emissions as determined in compliance with the ISO 14044 standard (ISO, 2006b) is provided for Scope 1 (direct GHG emissions), Scope 2 (indirect GHG emissions attributable to energy conversion processes) and Scope 3 (further GHG emissions from the supply chain)[3]. The results are illustrated in **Table 21**.

Scope 1: Direct GHG emissions occur from sources that are owned or controlled by the company, for example, emissions from combustion in owned or controlled boilers,

[2] The GHG Protocol is applicable to companies only.

[3] Detailed information about the standard and is application are available from www.ghgprotocol.org.

furnaces, vehicles, etc.; emissions from chemical production in owned or controlled process equipment.

Scope 2: Indirect GHG emissions from electricity are comprised of GHG emissions from the generation of purchased electricity consumed by the company. Purchased electricity is defined as electricity that is purchased or otherwise brought into the organizational boundary of the company. Scope 2 emissions physically occur at the facility where electricity is generated.

Scope 3: Other indirect GHG emissions are an optional reporting category that allows for the treatment of all other indirect emissions. Scope 3 emissions are a consequence of the activities of the company, but occur from sources not owned or controlled by the company. Some examples of Scope 3 activities are extraction and production of purchased materials; transportation of purchased fuels; and use of sold products and services.

Table 21: Scope 1, 2, and 3 GHG emissions for primary aluminum ingot production, representing 1000 kg of primary aluminum ingot.

Production Stages	Scope 1	Scope 2	Scope 3	Total
Bauxite (ton CO_2eq/ton Al)	0.05	0.02	0.01	0.08
Alumina (ton CO_2eq/ton Al)	1.26	0.12	0.84	2.22
Electrolysis (ton CO_2eq/ton Al)	2.35	3.77	0.39	6.51
Cast House (ton CO_2eq/ton Al)	0.07	0.05	0.01	0.13
Total (ton CO_2eq/ton Al)	3.73	3.96	1.25	8.94

5.1.3.4 Smog Formation Potential

The Smog Formation Potential (SFP), also called Photochemical Ozone Creation Potential (POCP), measures the emissions of precursors that contribute to low level smog (also called Summer Smog), produced by the reaction of NO_x and volatile organic compounds (VOC) under the influence of ultra violet light. SP is expressed as kg ozone (O_3) equivalent.

The SFP results are illustrated in **Figure 22** as well as in **Table 20**. The SFP related to the production of one metric ton of primary aluminum in North America is 446 kg O_3 equivalent. Smog formation potential for primary aluminum comes from NO_x emissions, which account for 99 percent of the SFP impact.

Like the other life cycle impact categories, the **electrolysis process** is the largest contributor to smog creation impacts, accounting for **55 percent** of the total SFP. This is followed by **alumina refining** which is responsible for **42 percent** of the net smog creation impact.

Approximately **70 percent** of these contributing emissions are associated with **production of electricity** required for primary aluminum ingot production.

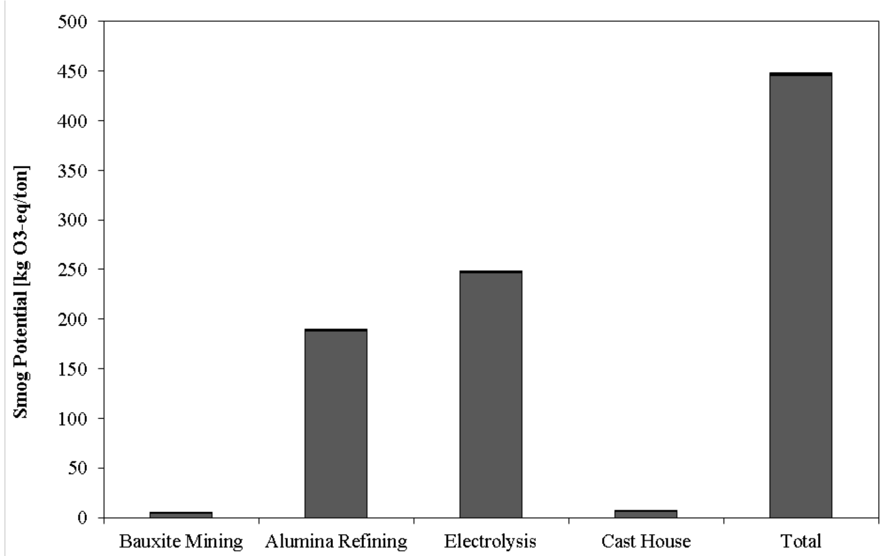

Figure 22: Smog formation potential results for primary aluminum ingot production. Electrolysis is the largest contributor to smog creation impacts, accounting for 55 percent of the total SFP, of which 70 percent are attributed to electricity production.

5.2 Aluminum Recycling (Secondary Production)

5.2.1 Process Descriptions and Models

Aluminum recycling, or secondary metal production, uses aluminum scrap as raw material. After scrap is “mined,” or collected, it is sorted and cleaned before it is used in metal production.

The core of secondary aluminum production is the melting and casting processes. Scrap is fed into melting furnaces to liquefy the metal. It is then purified, adjusted to the desired alloy, and produced into a form suitable for subsequent processing/fabrication. The kinds of furnaces involved in scrap melt include reverberatory, rotary, and electric furnaces.

The raw material can be categorized into “new” and “old” scrap.

New scrap, or post-industrial scrap, is generated from aluminum wrought and cast products as the metal is processed by fabricators into consumer or industrial products. All semi-fabrication, fabrication and/or final assembly processes generate scrap. The amount varies with application and characteristics of final products.

Old scrap is retrieved from post-consumer products or discarded products of all types. Common sources for old scrap include automobile parts such as car body sheet, bumpers, hoods, wheels, heat exchangers, and brakes; beverage cans; building and construction scrap such as aluminum door and window frames, siding, roofs, gutters, canopies, flag poles, furniture, enclosure rails, decorative pieces, cables and wires, and signs and boards; consumer durable goods or parts such as electronic product cases, sports and recreation equipment, water bottles, kitchen utensils, etc. (AA, 1998).

A quantitatively less important but symbolically significant source of secondary aluminum raw material source is dross and “salt cake”. Dross and salt cake are traditionally the kind of “waste” generated by either primary or secondary aluminum production facilities in which the processing of dross and salt cake is not an area of expertise. A number of aluminum recycling facilities in North America specialize in making metal from dross and concentrated salt cake. This is a new movement reflecting the industry’s commitment in improving production efficiency and reducing wastes.

5.2.1.1 Scrap Collection and Processing

5.2.1.1.1 Unit Process Description

Sources of scrap, unlike bauxite mines, are typically located in densely populated areas such as cities and suburbs. Additionally, there are no high-concentration deposits, as is the case with bauxite. The “deposits” are “retired” individual pieces of metal that are either attached to an object or facility or loosely scattered around.

Scrap collection in most cases involves the efforts of nearly all members of society, including children. Citizens are encouraged to identify retired or obsolete objects and recycle them, either on principle or for financial reward. Scrap "mining" is often considered a green-collar job, whose processes include largely manual and mechanical activities pertaining to collection, sorting, storage and transportation. The collection and transportation of aluminum scrap are often byproducts of other activities, such as shopping, home improvement, building demolition, auto repair and dismantling, garbage collection, etc.

After it is collected, scrap is sorted, cleaned and pre-processed. Scrap sorting involves separating aluminum from other materials and by the different alloy forms. Scrap cleaning involves the removal of oil, grease and other contaminants. Other standard processing steps include shredding and crushing, drying and sweating, and decoating or delacquering. Scrap processing helps reduce aluminum loss within the melting furnace and lowers emission of pollutants.

The unit process (as defined for this LCA study) begins with the shipment of scrap and ancillary materials to their storage areas on-site. The operations associated with this process include partial or all of the following:

- Shipping and handling of recovered and collected scrap and auxiliary material;
- Scrap separation including hand sorting, air classification, magnetic separation, eddy-current sorting, and/or heavy-media separation, etc.
- Scrap agglomeration including baler and/or briquetting;
- Scrap comminution/dismantling including shearing, shredding and/or crushing;
- Scrap cleaning, de-oiling, and/or drying;
- Scrap thermal processing including de-coating, de-lacquering, paint removal, partial melting and/or sweat melting, etc.;
- Recovery and handling of by-products of beneficial use;
- Maintenance and repair of plant and equipment; and
- Treatment of process air, liquids, and solids.

The output of this unit process is pre-processed "clean" aluminum scrap, or in some cases molten aluminum, transported or transmitted to a secondary aluminum production facility.

5.2.1.1.2 Source of Raw Materials and Energy

All aluminum scrap needed for secondary aluminum production in North America is sourced locally from industrial facilities, commercial facilities or municipal waste management facilities. The region itself is a net aluminum scrap exporter and ships about 2 millions metric tons in net amount of scrap to other regions each year.

Major energy carriers for scrap collection and processing include gasoline, diesel, natural gas and electricity. All energy is sourced locally where the processing activities occur.

5.2.1.1.3 Unit Process Inputs and Outputs

The unit process inputs and outputs are shown in **Table 22.**

Table 22: Inputs and outputs of aluminum scrap processing, representing 1000 kg of processed scrap.

Flow	Unit	Amount
Inputs		
Materials		
Unprocessed aluminum scrap [containing other objects]	kg	1042.45
Filter media [Operating materials]	kg	0.0011
Hydraulic oil [Operating materials]	kg	0.0266
Quicklime [Operating materials]	kg	0.8961
Lubricant (unspecified) [Operating materials]	kg	0.0094
Refractory [Operating materials]	kg	0.0738
Sodium silicate [Operating materials]	kg	0.3409
Water (fresh water) [Operating materials]	kg	1.4978
Energy		
Electricity	kWh	115.25
Natural gas [net calorific value]	MJ	896.99
Outputs		
Products		
Pre-processed aluminum scrap [Raw materials]	kg	1000
Waste for Recovery		
Fluff from shredder [Waste for recovery]	kg	4.6395
Steel scrap [Waste for recovery]	kg	4.0025
Other metal scrap [Waste for recovery]	kg	2.6073
Used oil [Waste for recovery]	kg	0.0306
Waste for Disposal		
Filter dust [Waste for disposal]	kg	1.3825
Refractory [Minerals]	kg	0.0051
Solid waste (unspecified) [Waste for disposal]	kg	7.1441
Baghouse lime [Inorganic emissions to industrial soil]	kg	0.0936
Emissions to Water		
Water (waste water, treated) [Treated waste water release]	kg	1.0449

5.2.1.2 Scrap Melting and Ingot Casting

5.2.1.2.1 Unit Process Description

Aluminum scrap melting is the process of feeding processed scrap into furnaces to liquefy the metal. And ingot casting is the process of purifying the molten metal, adjusting it to a variety of desired alloys, and casting it into desired shapes for subsequent fabrication.

5.2.1.2.1.1 Melting

Scrap melting is carried out in furnaces at temperatures ranging from 1,300 to 1,500 degrees Fahrenheit, or 700 to 815 degrees Celsius. There are a variety of types of furnaces used in melting scrap including reverberatory furnace, rotary furnace, crucible furnace, and electric furnace.

Reverberatory and rotary furnaces are the most common types of furnaces used to melt or remelt many different grades of aluminum scrap. These types of furnaces are usually gas fired and usually range in capacity from 30,000 to 250,000 pounds, or 15 to 125 metric tons. Depending on the design, reverberatory furnaces can also be divided into single-chamber and multiple-chamber furnaces. Rotary furnaces are used to melt highly oxidized scrap during which salt flux is used to remove the oxidized waste.

Crucible furnaces are usually used for very small melting operations and electric furnaces use electricity in stead of gas fire to melt scrap.

Salt is sometimes used to “flux” the molten aluminum during the aluminum scrap melting process in which the feedstock is partially oxidized or highly impure. The salt is a mixture of sodium and potassium chloride with several percent of cryolite (Na_3AlF_6) added. The salt flux has several purposes. First, it minimizes the amount of air contacting the molten metal and reduces the loss of metal by oxidation. It also servers as a carrier of the cryolite to the surface of the scrap charge, where it removes the aluminum oxide skin on the metal scrap. This enables the molten metal to agglomerate and subsequently settle out beneath the salt/scrap furnace charge, resulting in higher metal recoveries and cleaner aluminum.

Most aluminum scrap melting facilities use a batch approach in melting operations. In some cases, one large melting reverberatory furnace is used to support the flow requirements for two smaller holding furnaces. The melting furnace would be used to melt the scrap, flux the molten metal, change its alloy, and remove impurities or unwanted elements. Following these steps, the molten metal is transferred to a holding furnace. In this furnace, final alloying and any additional operations are completed to ensure that the metal meets its desired specifications.

Depending on the composition of the scrap, the resultant molten aluminum may require additional processing to ensure strict customer metal quality specifications. Fluxing is the most used method. Fluxing involves the injection of gases such as chlorine, nitrogen, or argon below the surface to react with contaminants and/or raise them to the surface for skimming.

5.2.1.2.1.2 Alloying

Once contaminants are removed, the metal may require the addition of other elements to meet the final product specification. Alloying is the process by which the chemistry of the metal is modified through the addition of such elements. Copper, magnesium, silicon and zinc are the most common alloying agents used in aluminum recycling. Iterative chemical analyses of the furnace bath are taken while the alloying agents are added until the correct alloy is achieved.

Once melted and alloyed to the proper chemistry, the metal may be shipped in molten form or cast into ingot, bars, shot, billet, cones, or sows for subsequent use. There are several routes for further processing the resulting metal. The particular route depends on product and customer specifications.

5.2.1.2.1.3 Casting

Ingot is formed by the casting of molten metal into molds. Ingots may be formed by direct chill (DC) casting or by pouring into shallow molds. The form depends on the ultimate use of the metal.

5.2.1.2.1.4 Emissions

Dust generation and air emissions are typical at both scrap processing and melting facilities. Chloride gases, volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs—note: PAHs are a category of VOC) are representative substances emitted from these facilities as a result of scrap de-lacquering and evaporation of fluxing salt. Great effort has been made in the industry to ensure full compliance with the Clean Air Act and other relevant environmental laws and regulations. Modern furnace and equipment designs enable most air emissions to be confined and circulated inside the equipment so that they can be fully combusted, improving energy efficiency. Scrubbers and bag houses are also commonly used to control emissions and dust. Lime or calcium carbonate is used to capture both chloride gases and residue VOCs.

5.2.1.2.1.5 Unit Process Description Summary

To summarize, the aluminum scrap melting and ingot casting unit process (as defined for this LCA study) begins with the shipment of pre-processed scrap and other materials to their storage areas on-site. The operations associated with this process include:

- Shipment and handling of pre-treated scrap and ancillary materials;
- Melting scrap, and refining and purification of molten metal;
- Batching, metal treatment, and casting operations;
- Homogenizing, sawing, and packaging;
- Recovery and handling of internal process scrap;
- Maintenance and repair of plant and equipment; and
- Treatment of process air, liquids, and solids.

The output of this unit process is packaged secondary/recycled aluminum ingots transported to an aluminum fabricating facility.

5.2.1.2.2 Source of Raw Material and Energy

The source of major raw materials for this unit process is the pre-treated aluminum scrap – the output of the previous unit process. Most facilities process un-treated scrap on site, while others purchase processed scrap from specialized scrap processers. The source of auxiliary materials is mostly domestic and/or local.

Almost all secondary metal production facilities in North America use natural gas and electric power as the primary sources of energy. Electric furnaces use electric power as their major energy source. Unlike primary aluminum producers, most secondary aluminum producers in North America do not purchase electricity from specific power generators, nor do they own any power generators. In stead, they purchase their power from local utility companies.

5.2.1.2.3 Unit Process Inputs and Outputs

The unit process inputs and outputs for both aluminum recycling and secondary ingot production are shown in **Table 23**and **Table 24**, respectively.

Please note that the inputs and outputs of this unit process are given in two different formats, namely ***aluminum recycling*** and ***secondary aluminum production***. The difference of the two formats is in the involvement of primary aluminum metal and alloying elements. The *aluminum recycling* dataset does not involve in the addition of primary metal and alloying elements while the *secondary aluminum production* dataset does so. The purpose of the two different formats is to provide users information for different uses or different modeling practices. It is highly recommended that users of the datasets choose the appropriate format to do their studies.

The aluminum recycling format, as shown in **Table 23**, is provided for users to:

- ***Conduct life cycle assessment studies by taking an Avoided Burden, or closed-loop approach, as described in Section 4.1. The Avoided Burden approach is the recommended methodology by the Aluminum Association for evaluating aluminum products. Users should only use this dataset to conduct their study;***
- ***Calculate "cradle-to-gate" inventory when the involvement of primary metal is completely separated from recycled metal; and***
- ***Evaluate the environmental benefits of aluminum recycling. Recycling aluminum helps eliminate the need for primary metal production and therefore saves natural resources and energy and avoids emissions and wastes. To accurately evaluate the benefit of recycling, this dataset shall be used to prevent double counting.***

This data format is assuming that aluminum products are recycled in a carefully and finely sorted manner, almost equivalent to a "closed-loop" recycling in which the same alloy products are sorted together and recycled into the same alloy. There is no involvement of primary metal and alloying elements in this case. The resulted metal is either not adjusted into special specifications or there is no need for adjustment. This is technologically feasible and a proportion of the recycling industry carries out its production in this manner.

The secondary aluminum production format, as shown in **Table 24**, is provided for users to:

- ***Conduct life cycle assessment studies by taking a Recycled Content approach; and/or***
- ***Calculate the "cradle-to-gate" inventory of aluminum products (note: it is also possible to use the "Aluminum Recycling" format to do so if the involvement of primary metal is completely separated from recycled metal).***

This format is assuming that aluminum products are recycled in a none-sorted, or highly mixture manner in which different alloys and product categories are mixed together, as is widely in practice in today's recycling processes. In this case, certain amount of primary aluminum metal and alloying elements are used to adjust the alloy compositions to the required specifications. The added primary metal and alloying agents here carry a "cradle-to-gate" burden tracing back to the mining process.

Table 23: Inputs and outputs of aluminum recycling – scrap melting and ingot casting process, representing 1000 kg of recovered aluminum.

Flow	Unit	Amount
Inputs		
Materials		
Processed aluminium scrap [Metals]	kg	1047.51
Argon [Inorganic operating materials]	kg	0.4666
Chlorine [Inorganic operating materials]	kg	2.0646
Cryolite [Inorganic operating materials]	kg	0.5725
Filter media [Operating materials]	kg	0.1163
Hydraulic oil [Operating materials]	kg	0.0437
Quicklime [Minerals, operating materials]	kg	3.9872
Lubricant (unspecified oil) [Operating materials]	kg	0.029
Nitrogen [Inorganic operating materials]	kg	16.2689
Oxygen gaseous [Inorganic operating materials]	kg	0.1566
Potassium chloride [Inorganic operating materials]	kg	5.6957
Refractory [Minerals, operating materials]	kg	1.233
Sodium chloride (salt) [Inorganic operating materials]	kg	10.7161
Caustic soda (100%) [Inorganic operating materials]	kg	0.1918
Sulphuric acid (96%) [Inorganic operating materials]	kg	0.0303
Plastic packaging [Operating materials]	kg	0.012
Steel packaging [Operating materials]	kg	0.0913
Wood packaging [Resources]	kg	0.3554
Water (fresh water) [Water]	kg	331.175
Energy		
Electricity [Electric power]	kWh	110.324
Thermal energy from natural gas [net calorific value]	MJ	4789.42

Outputs		
Products		
Aluminium ingot (secondary) [Metals, products]	kg	1000
Waste for Recovery		
Other metal scrap [Waste for recovery]	kg	0.7592
Dross [Waste for recovery]	kg	67.2575
Saltcake [Waste for recovery]	kg	15.888
Used oil [Waste for recovery]	kg	0.0555
Waste for Disposal		
Filter dust [Waste for disposal]	kg	7.2173
Refractory [Waste for disposal]	kg	1.33
Solid waste [waste for disposal]	kg	0.0262
Saltcake [Waste for disposal]	kg	20.132
Emissions to Water		
Water (Treated waste water) [Treated waste water for release]	kg	25.9574
Chloride [Inorganic emissions to fresh water]	kg	0.02272
Chemical oxygen demand (COD) [Analytical measures to fresh water]	kg	0.00121
Biological oxygen demand (BOD) [Analytical measures to fresh water]	kg	0.00032
Heavy metals to water (unspecified) [Heavy metals to water]	kg	5.30E-05
Emissions to Air		
Carbon dioxide [Inorganic emissions to air]	kg	0.00729
Chlorine [Inorganic emissions to air]	kg	0.00237
Dust [Particles to air]	kg	0.2829
Hydrogen chloride [Inorganic emissions to air]	kg	0.0881
Hydrogen fluoride [Inorganic emissions to air]	kg	0.02577
Lead (+II) [Heavy metals to air]	kg	0.00108
Mercury (+II) [Heavy metals to air]	kg	7.96E-08
Methane [Organic emissions to air (group VOC)]	kg	0.00039
Nitrogen dioxide [Inorganic emissions to air]	kg	0.21237
Nitrous oxide (laughing gas) [Inorganic emissions to air]	kg	0.00037
Sulphur dioxide [Inorganic emissions to air]	kg	0.02377
VOC (unspecified) [Organic emissions to air (group VOC)]	kg	0.0882
Emissions to Soil		
Aluminium [Inorganic emissions to industrial soil]	kg	0.0763
Copper (+II) [Heavy metals to industrial soil]	kg	0.0021
Lead (+II) [Heavy metals to industrial soil]	kg	3.81E-05
Zinc (+II) [Heavy metals to industrial soil]	kg	0.00127

Table 24: Inputs and outputs of secondary aluminum ingot production – scrap melting and ingot casting process, representing 1000 kg of secondary aluminum ingot.

Flow	Unit	Amount

Inputs		
Materials		
Alloy elements [Metals]	kg	14.5028
Primary aluminum ingot [Metals]	kg	65.4195
Processed aluminium scrap [Metals]	kg	967.592
Argon [Inorganic operating materials]	kg	0.4666
Chlorine [Inorganic operating materials]	kg	2.0646
Cryolite [Inorganic operating materials]	kg	0.5725
Filter media [Operating materials]	kg	0.1163
Hydraulic oil [Operating materials]	kg	0.0437
Quicklime [Minerals, operating materials]	kg	3.9872
Lubricant (unspecified oil) [Operating materials]	kg	0.029
Nitrogen [Inorganic operating materials]	kg	16.2689
Oxygen gaseous [Inorganic operating materials]	kg	0.1566
Potassium chloride [Inorganic operating materials]	kg	5.6957
Refractory [Minerals, operating materials]	kg	1.233
Sodium chloride (salt) [Inorganic operating materials]	kg	10.7161
Caustic soda (100%) [Inorganic operating materials]	kg	0.1918
Sulphuric acid (96%) [Inorganic operating materials]	kg	0.0303
Plastic packaging [Operating materials]	kg	0.012
Steel packaging [Operating materials]	kg	0.0913
Wood packaging [Resources]	kg	0.3554
Water (fresh water) [Water]	kg	331.175
Energy		
Electricity [Electric power]	kWh	110.324
Thermal energy from natural gas [net calorific value]	MJ	4789.42
Outputs		
Products		
Aluminium ingot (secondary) [Metals, products]	kg	1000
Waste for Recovery		
Other metal scrap [Waste for recovery]	kg	0.7592
Dross [Waste for recovery]	kg	67.2575
Saltcake [Waste for recovery]	kg	15.888
Used oil [Waste for recovery]	kg	0.0555
Waste for Disposal		
Filter dust [Waste for disposal]	kg	7.2173
Refractory [Waste for disposal]	kg	1.33
Solid waste [waste for disposal]	kg	0.0262
Saltcake [Waste for disposal]	kg	20.132
Emissions to Water		
Water (Treated waste water) [Treated waste water for release]	kg	25.9574
Chloride [Inorganic emissions to fresh water]	kg	0.02272

Chemical oxygen demand (COD) [Analytical measures to fresh water]	kg	0.00121
Biological oxygen demand (BOD) [Analytical measures to fresh water]	kg	0.00032
Heavy metals to water (unspecified) [Heavy metals to water]	kg	5.30E-05
Emissions to Air		
Carbon dioxide [Inorganic emissions to air]	kg	0.00729
Chlorine [Inorganic emissions to air]	kg	0.00237
Dust [Particles to air]	kg	0.2829
Hydrogen chloride [Inorganic emissions to air]	kg	0.0881
Hydrogen fluoride [Inorganic emissions to air]	kg	0.02577
Lead (+II) [Heavy metals to air]	kg	0.00108
Mercury (+II) [Heavy metals to air]	kg	7.96E-08
Methane [Organic emissions to air (group VOC)]	kg	0.00039
Nitrogen dioxide [Inorganic emissions to air]	kg	0.21237
Nitrous oxide (laughing gas) [Inorganic emissions to air]	kg	0.00037
Sulphur dioxide [Inorganic emissions to air]	kg	0.02377
VOC (unspecified) [Organic emissions to air (group VOC)]	kg	0.0882
Emissions to Soil		
Aluminium [Inorganic emissions to industrial soil]	kg	0.0763
Copper (+II) [Heavy metals to industrial soil]	kg	0.0021
Lead (+II) [Heavy metals to industrial soil]	kg	3.81E-05
Zinc (+II) [Heavy metals to industrial soil]	kg	0.00127

5.2.1.3 Dross and Salt cake Recycling

5.2.1.3.1 Unit Process Description

A by-product of the aluminum scrap melting and ingot casting process is dross or skim. This is formed when molten aluminum is exposed to air and reacts with oxygen and moisture in the air, forming aluminum oxide. Any facility that melts aluminum will inevitably generate some form of dross, although the amount of dross generated depends on furnace type, condition of the feedstock, and operating practice. The metal content of dross varies widely and can range from 5 to 80 percent.

Salt cake is a residue from salt flux and it is composed of the spent flux oxides and other oxides and impurities from the melt process. Like dross, this residue also floats on top of molten metal and can be separated. Salt cake typically contains 3 to 5 percent metal.

Dross and salt cake are traditional solid waste of aluminum recycling process. However, the aluminum industry makes significant effort and progress during the past two decades to retrieve both the metal content and the salts for reuse, and thereby reducing the amount of solid waste generated from recycling facilities. As a result, a specific recycling industry has been developed to specialize in dross and salt cake recycling. There are a couple of recycling companies who have dedicated facilities to specialized in dross and salt cake recycling. These facilities take in a large amount of dross and salt cake from other companies and facilities and use it as part of their feedstock to extract metal and salt. Many secondary aluminum production facilities have the capability of recycling both scrap and dross and salt cake.

Dross and salt cake can be recycled in either hot or cooled-down status. Hot status recycling can only be done in a facility where it has dross and salt cake processing capacity. Hot status recycling refers to the handling and remelting of dross or salt cake on site soon after they were skimmed off from molten metal from a melting furnace. Since the metallic content is still hot or molten, the recycling would need less energy. Cooled-down status recycling refers to the recycling of dross and salt cake after they were completely cooled down. The cooling of dross involves operations that help prevent metal from oxidization and reduction of the sizes of the solid. A rotary cooling device is often used with an argon or nitrogen environment being created to prevent metal from oxidizing.

The recycling of dross and salt cake may start with a "concentration" process designed to separate solids of high aluminum metallic content from other chemicals such as oxidized aluminum, salt and other contaminants. This is mainly done through crushing, milling and screening. As a result, larger size particles contain high metallic content and are subsequently charged into melting furnaces, and very small size particles are mostly salt or oxidized aluminum, which are further processed to extract salt for reuse.

The fundamental step of dross and salt cake recycling is the remelting. This is similar to scrap melting and rotary furnaces or tiltable rotating barrel furnaces are used (Schlesinger, 2007). Salt is normally added to separate aluminum from contaminants and the composition of salt is similar to that used in scrap melting in rotary furnaces.

Melting residues generated from dross and salt cake recycling process are called non-metallic product (NMP). This is often landfilled at designated locations or can be used as feedstock in cement kilns.

In summary, the dross and salt cake recycling unit process begins with the shipment of dross/salt cake and other process materials to their storage areas on-site. The operations associated with this process include:

- Shipment and handling of dross, salt cake and ancillary materials;
- Crushing, milling and screening to separate metallic contents from salts and oxidized contents;
- Melting the pre-processed metallic dross and dross concentrates, and refining and purification of molten metal;
- Batching and casting operations;
- Extraction of salt from residues;
- Sawing, and packaging;
- Maintenance and repair of plant and equipment; and
- Treatment of process air, liquids, and solids.

The output of this unit process is packaged recycled aluminum ingots transported to a remelting facility.

5.2.1.3.2 Source of Raw Materials and Energy

The source of raw materials for this unit process is the production waste of recycling/secondary aluminum production from aluminum scrap melting furnaces. The raw material may also be from primary aluminum smelting facilities. In all cases, the raw materials are all from North America, usually from the nearest secondary or primary smelting facilities. The source of auxiliary materials is mostly domestic and/or local.

Natural gas and electric power are the primary sources of energy. Unlike primary aluminum producers, most secondary aluminum producers in North America do not purchase electricity from specific power generators, nor do they own any power generators. In stead, they purchase their power from local utility companies.

5.2.1.3.3 Unit Process Inputs and Outputs

The unit process inputs and outputs are shown in **Table 25**.

Table 25: Inputs and outputs of dross and salt cake recycling process, representing 1000 kg of recovered aluminum

Flow	Unit	Amount
Inputs		
Materials		
Concentrated dross and saltcake (feedstock) [Waste for recovery]	kg	2689.787
Argon [Inorganic intermediate products]	kg	17.5405
Sodium chloride (rock salt) [Inorganic intermediate products]	kg	158.1632
Potassium chloride [Inorganic intermediate products]	kg	52.8181
Cryolite [Inorganic intermediate products]	kg	2.7505
Refractory [Minerals]	kg	0.6258
Quicklime [Minerals]	kg	15.9813
Energy		
Electricity [Electric power]	kWh	210.3
Thermal energy from natural gas (MJ) [Thermal energy]	MJ	5929.489
Outputs		
Products		
Aluminium ingot (recycled) [Metals]	kg	1000
Waste for Recovery		
Used oil [Waste for recovery]	kg	0.1461
Waste for Disposal		
Aluminium oxide residue [Waste for disposal]	kg	103.6887
Filter dust [waste for disposal]	kg	68.3085
Refractory [waste for disposal]	kg	2.6051

Saltcake [Waste for disposal]	kg	1474.117
Emissions to Air		
Dust [Particles to air]	kg	0.2421
Hydrogen chloride [Inorganic emissions to air]	kg	0.07507
Hydrogen fluoride [Inorganic emissions to air]	kg	0.02046
Lead (+II) [Heavy metals to air]	kg	0.00005
Nitrogen dioxide [Inorganic emissions to air]	kg	0.0242
Sulphur dioxide [Inorganic emissions to air]	kg	0.1441
VOC (unspecified) [Organic emissions to air (group VOC)]	kg	0.0798

5.2.2 LCI Results of Aluminum Recycling and Secondary Aluminum Ingots

This section presents the most important LCI results of aluminum recycling and secondary aluminum ingot production in the North America region. The models used to calculate the LCI are shown in **Figure 23** and **Figure 24**. The results of the LCI are shown in **Table 26**. The breakdowns of primary energy demand and carbon dioxide emissions for both scenarios are shown in **Table 27**and **Table 28**. Analysis of the two particular parameters is shown in the subsections followed.

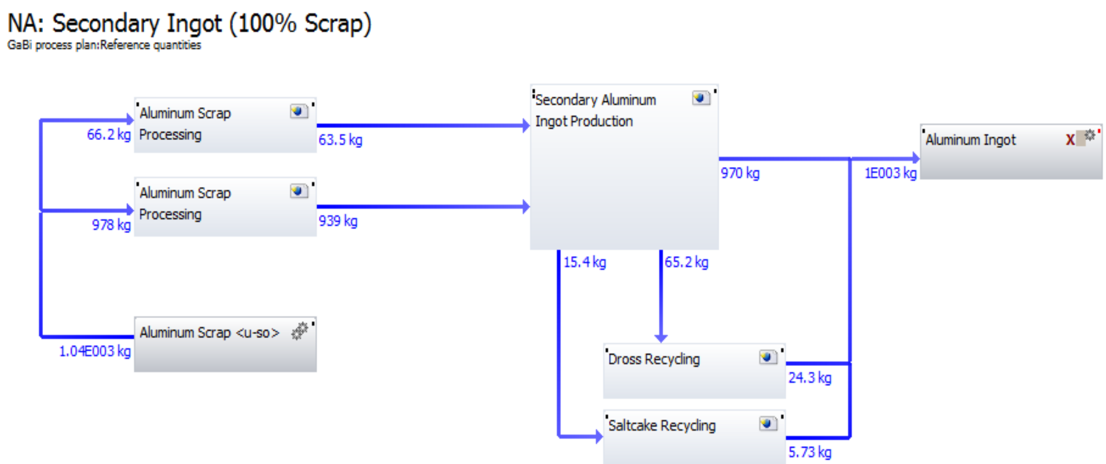

Figure 23: Illustration of the aluminum recycling model, representing 1000 kg of recovered aluminum

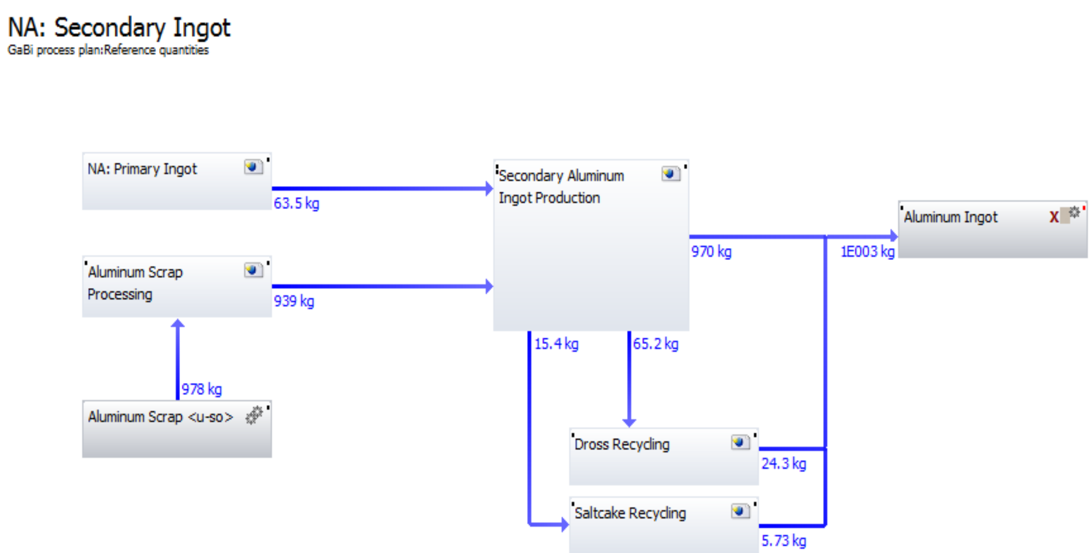

Figure 24: Illustration of the secondary aluminum production model, representing 1000 kg of aluminum ingot.

Table 26: LCI of aluminum recycling and secondary aluminum production, representing 1000 kg of aluminum ingot.

Inventory Category	Aluminum Recycling (100% scrap)	Secondary Ingot (primary metal and alloy added)
Energy (MJ)		
Non-renewable energy	1.02E+04	1.57E+04
Hydroelectric energy	7.79E+02	3.90E+03
Other renewable energy	1.19E+02	1.59E+02
Resources (kg)		
Bauxite	9.16E+01	4.84E+02
Net Process Water	306	712
Air Emissions (kg)		
Carbon dioxide	6.34E+02	1.13E+03
Carbon monoxide	3.35E-02	2.73E-01
Chlorine	2.32E-03	2.35E-03
Flourine/Fluorides	7.72E-03	4.26E-02
Hydrogen chloride	9.69E-02	1.27E-01
Hydrogen fluoride	3.43E-02	7.29E-02
Nitrogen oxides	8.47E-01	1.97E+00
Nitrous oxide	6.49E-03	1.27E-02
Sulphur oxides	1.18E+00	3.86E+00
Non-methane VOCs	2.19E-01	2.93E-01
Methane	1.06E+00	1.89E+00
Dust (PM10)	2.81E-01	2.81E-01
Dust (PM2.5)	4.66E-02	1.37E-01
Water Emissions (kg)		
Biological oxygen demand (BOD)	5.91E-03	7.47E-03
Chemical oxygen demand (COD)	1.14E-01	1.93E-01
Heavy metals	1.05E+00	5.26E+00
Ammonia	4.93E-05	2.10E-04
Flourine/Flourides	1.79E-01	2.69E-01
Phosphate	9.27E-05	1.91E-04
Solid Waste (kg)		
Total waste (excluding overburden)	139.3066845	349.4334978

Table 27: Breakdown of primary energy demand and CO_2 emissions of aluminum recycling by unit processes, representing 1000 kg of recovered aluminum

Inventory Parameter	Unit	Scrap Collection and Processing	Scrap Melting and Casting	Dross & Salt Cake Recycling	Primary Ingot	Total

Primary Energy Demand	GJ/ton	2.01	8.62	0.33	0.00	10.95
Non renewable	GJ/ton	1.92	7.82	0.32	0.00	10.06
Renewable	GJ/ton	0.08	0.80	0.01	0.00	0.89
CO_2 emissions	ton CO_2/ ton	0.11	0.50	0.02	0.00	0.63

Table 28: Breakdown of primary energy demand and CO_2 emissions by unit processes for secondary aluminum production, representing 1000 kg of secondary aluminum ingot

Inventory Parameter	Unit	Scrap Collection and Processing	Scrap Melting and Casting	Dross & Salt Cake Recycling	Primary Ingot	Total
Primary Energy Demand	GJ/ton	2.01	8.62	0.33	8.76	19.72
Non renewable	GJ/ton	1.92	7.82	0.32	5.60	15.66
Renewable	GJ/ton	0.08	0.80	0.01	3.16	4.05
CO_2 emissions	ton CO_2/ ton	0.11	0.50	0.02	0.50	1.13

5.2.2.1 Primary Energy Demand

As it is shown in **Figure 25**, the majority of PED for aluminum recycling is associated with scrap melting and casting. This unit process accounts for 79 percent of the total energy demand. Also showing in the figure is that the majority (92 percent) of PED is from non-renewable energy source.

For secondary aluminum ingot (**Figure 26**), however, the addition of primary ingot contributes to 44 percent of total primary energy demand and the melting and casting of metal contributes to another 44 percent of the total PED. Similar to the recycling scenario, the majority (79 percent) of energy is from non-renewable source.

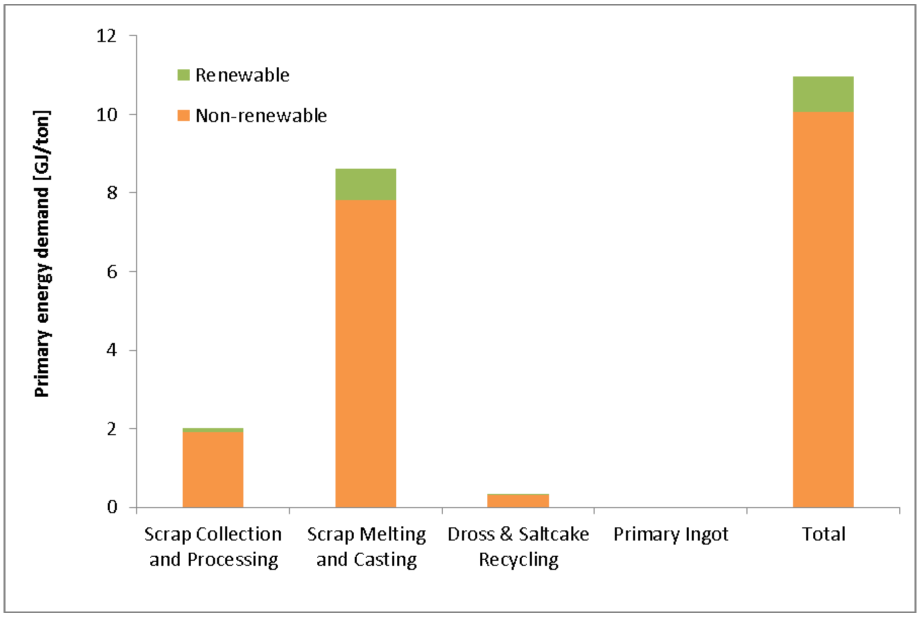

Figure 25: Primary energy demand of aluminum recycling, representing 1000 kg of recovered aluminum

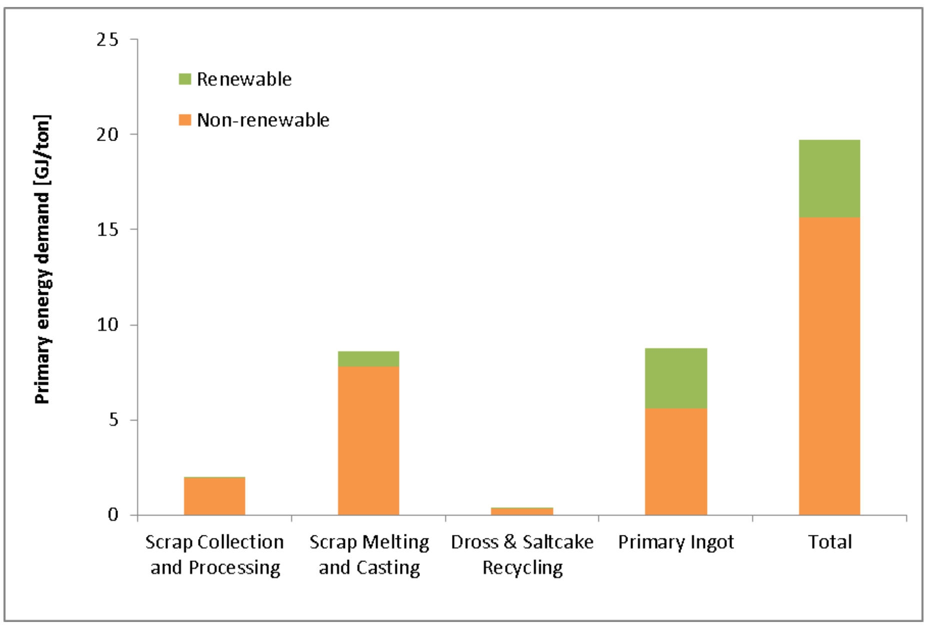

Figure 26: Primary energy demand of secondary aluminum ingot, representing 1000 kg of secondary aluminum ingot

5.2.2.2 Carbon Dioxide Emissions

Similar to PED, as it is shown in **Figure 27**, the majority of CO_2 emissions for aluminum recycling is associated with scrap melting and casting. This unit process contributes 80 percent of the total emissions.

For secondary aluminum ingot (**Figure 28**), however, the addition of primary ingot contributes to 44 percent of total CO_2 emissions and the melting and casting of metal contributes to another 44 percent of the total emissions.

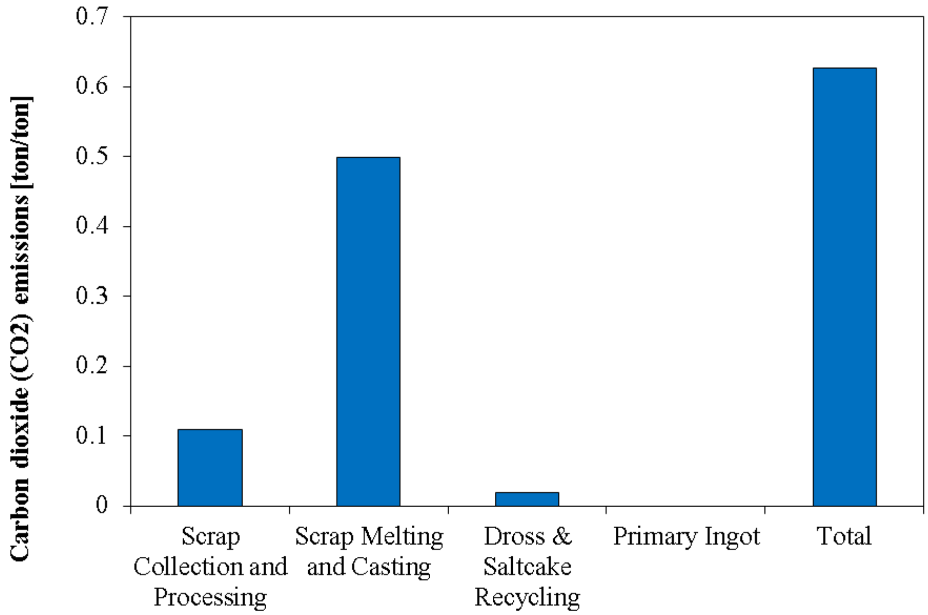

Figure 27: Carbon dioxide emissions associated with aluminum recycling, representing 1000 kg of recovered aluminum

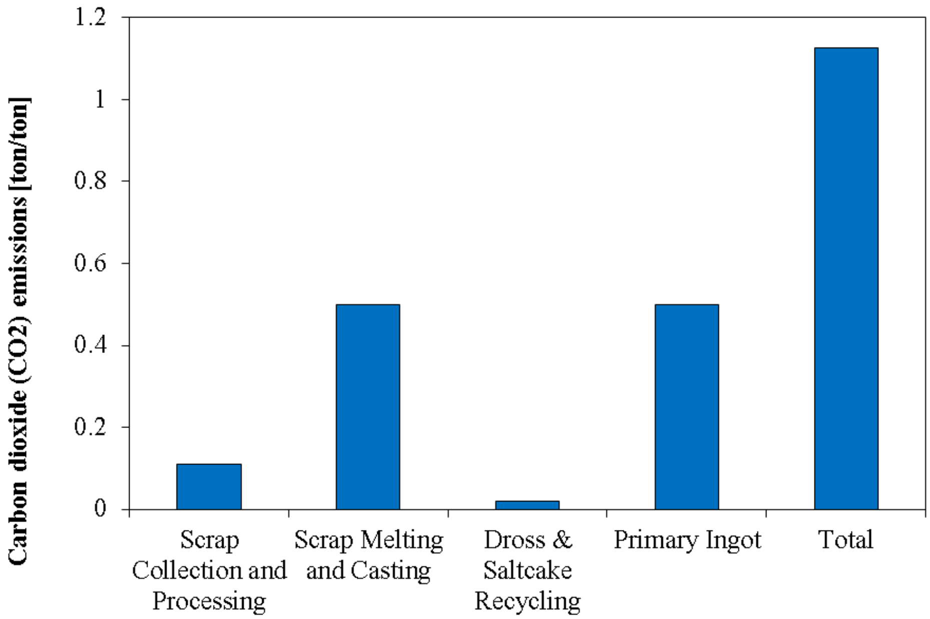

Figure 28: Carbon dioxide emissions associated with secondary aluminum ingot production, representing 1000 kg of secondary aluminum ingot

5.2.3 LCIA Results

The LCIA results of aluminum recycling and secondary aluminum production are presented in **Table 29** and **Table 30**, respectively. The results represent the output of 1 metric ton of metal in North America.

Table 29: LCIA results for aluminum recycling, representing 1000 kg of recovered aluminum in North America.

Impact Assessment Category	Unit	Scrap Collection and Processing	Scrap Melting and Casting	Dross and Saltcake Recycling	Primary Ingot	Total
Primary Energy Demand	GJ/ton	2.01	8.62	0.33	0.00	10.95
Global Warming Potential	ton CO_2-eq/ton	0.11	0.53	0.02	0.00	0.67
Acidification Potential	kg SO_2-eq/ton	0.305	1.705	0.052	0.000	2.063
Eutrophication Potential	kg N-eq/ton	0.010	0.003	0.055	0.000	0.068
Smog Formation Potential	kg O_3-eq /ton	3.15	20.92	0.77	0.00	24.83

Table 30: LCIA results for secondary aluminum production, representing 1000 kg of secondary aluminum ingot in North America.

Impact Assessment Category	Unit	Scrap Collection and Processing	Scrap Melting and Casting	Dross and Saltcake Recycling	Primary Ingot	Total
Primary Energy Demand	GJ/ton	2.01	8.62	0.33	0.00	10.95
Global Warming Potential	ton CO_2-eq/ton	0.11	0.53	0.02	0.57	1.23
Acidification Potential	kg SO_2-eq/ton	0.305	1.705	0.052	3.582	5.644
Eutrophication Potential	kg N-eq/ton	0.010	0.003	0.055	0.062	0.129
Smog Formation Potential	kg O_3-eq /ton	3.15	20.92	0.77	28.28	53.11

5.3 Aluminum Semi-Fabrication

There is no functional difference between primary and secondary aluminum; both virgin and secondary aluminum can be manufactured into semi-fabricated or final products. Aluminum semi-fabrication involves rolling, extrusion, shape-casting, or other methods. The processes and technologies involved are extremely diversified and can be done on a very large scale (in the case of rolling and extrusion) or in small mom-and-pop shops (in the case of shape-casting).

Issues of concern during semi-fabrication are energy consumption, process material utilization efficiency, and environmental releases.

Energy consumption in the fabrication processes in North America involves mainly natural gas and electricity. The amount of energy used per ton of aluminum product fabrication varies depending on the specific form of fabrication, the technology employed, and the scale of the operation. A large proportion of energy is used to heat or melt the metal during fabrication. For this reason, large integrated aluminum producers are able to save more energy than small independent fabricators by streamlining the production processes in the same facility to avoid the ingot casting and re-melting processes.

Emissions and wastes are a less prominent problem in the aluminum fabrication processes than in the resource extraction and material production processes because the amounts are relatively smaller.

5.3.1 Fabrication Processes

5.3.1.1 Extrusion

5.3.1.1.1 Process Description

The extrusion process takes cast extrusion billet (round bar stock produced from direct chill molds) and produces extruded shapes. The process begins with an inline preheat that takes the temperature of the billet to a predetermined level depending on the alloy. The billet is then sheared if not already cut to length and deposited into a hydraulic press. The press squeezes the semi-plastic billet through a heated steel die that forms the shape. The shape is extruded into lengths defined by the take-off tables and is either water quenched or air cooled. The shape is then clamped and stretched to form a solid straightened length (AA, 1998).

The straighten lengths are cut to final length multiples and may be placed in an aging furnace to achieve a desired temper. Lengths are then finished (drilled and shaped) and placed into a coating process. The types of coatings include anodized, painted, and lacquered finishes.

There are over 100 extrusion plants in North America. The technology is relatively mature and variation in process efficiency is minor.

Depending on the shape and desired performance characteristics of the extrusion, some profiles are put through an impact extruding process which forms the final parts using considerably higher pressures.

This unit process (as defined for this LCA study) begins with the shipment of process materials to their storage areas on-site. The operations associated with this process include:

- Shipment and handling of cast extrusion ingots and billets and auxiliary material;
- Preheating and cutting or shearing of billet lengths;
- Extruding of shapes, cooling, stretching and cutting;
- Heat treating, aging, anodizing or painting;
- Finishing and packaging activities;
- Recovery and handling of internal process scrap;
- Recovery and handling of other by-products of beneficial use;
- Maintenance and repair of plant and equipment; and
- Treatment of process air, liquids, and solids.

The output of this unit process is semi-fabricated and surface finished extrusion products transported to a component or final product manufacturer.

5.3.1.1.2 Source of Raw Materials and Energy

Source of major raw material for this unit process is aluminum ingots, usually containing both primary and secondary metal contents.

As it is stated in Section 5.1.1.4.4, the large majority of primary metal consumption in North America is domestically made in the region and there is a small quantity of primary metal imports, however, there is also a similar quantity of primary metal exports. As a result, North America ended in 2010 as a net primary aluminum exporter. For this reason, we assume that all primary aluminum ingots used for the extrusion process are sourced from domestic producers.

Similarly, it is assumed that all secondary aluminum ingots used for extrusion are sourced from domestic producers in 2010.

Auxiliary materials in this unit process are either sourced from domestic producers or from imports. The quantity of these materials, however, is very small and we assume that all of them are sourced domestically.

Both natural gas and electricity are sourced domestically. Most aluminum extruders in North America do not purchase electricity from specific power generators, nor do they own any power generators. In stead, they purchase their power from local utility companies.

Based on our survey results, extruded aluminum products made in North America contains a considerable proportion of recycled aluminum. The metal composition of extrusion products, based on metal feedstock information collected at the melting furnaces for extrusion billet making, is shown in **Table 31**.

Table 31: Metal composition of extruded aluminum products in North America

Category of Metal Source	Percentage
Primary Metal (including alloying agents)	47
Recovered Aluminum from Internal Process (Run-Around) Scrap	5
Recovered Aluminum from Post-Industrial Scrap	19
Recovered Aluminum from Post-Consumer Scrap	29

Note:

- *This information is based on reports from individual facilities regarding to the metal feedstock at smelters or melting furnaces for extrusion billet making;*
- *The information represents 723,116 metric tons of reported production, or 59 percent of the industry's total producer shipment in 2010.*
- *The percentage is given as a weighted average based on production volumes of each facility;*
- *Assumptions were made to calculate the results due to the fact that, although in a smaller amount, there was a category of reported metal in which the exact source of the metal can not be identified;*
- *Definitions of Internal Process (Run-Around) Scrap, Post-Industrial Scrap and Post-Consumer Scrap are consistent with ISO 14021/25 (2006) on environmental labels and declarations, and the related interpretations by UL Environment;*
- *Products shipped to different market sectors may vary significantly on its metal compositions;*
- *Due to the involvement of assumptions for the calculations, this information can only be deemed as the best estimates from the industry.*

5.3.1.1.3 Unit Process Inputs and Outputs

The unit process inputs and outputs are listed in **Table 32**.

Table 32: Unit process inputs and outputs of aluminum extrusion, representing 1000 kg of extruded and surface finished (anodized or coated) products.

Flow	Unit	Amount

Inputs		
Materials		
Aluminium ingot (primary, including alloy agents) [Metals]	kg	604.512
Aluminium ingot (recycled, 100% scrap) [Metals]	kg	685.541
Hydraulic oil [Operating materials]	kg	0.3268
Lubricant (unspecified oil) [Operating materials]	kg	0.1134
Chromium [Operating materials]	kg	0.0332
Paint (coating paint) [Operating Materials]	kg	2.1885
Solvent [Operating materials]	kg	1.4003
Caustic soda (100%) [Operating materials]	kg	3.8933
Sulphuric acid (96%) [Operating materials]	kg	1.3286
Cardboard [Materials for packaging]	kg	0.5626
Paper packaging [Materials for packaging]	kg	1.8953
Plastic packaging [Materials for packaging]	kg	0.3485
Steel packaging [Materials for packaging]	kg	0.7648
Wood packaging [Materials for packaging]	kg	11.9436
Water (fresh water) [Operating materials]	kg	499.904
Energy and Fuels		
Electricity [Electric power]	kWh	196.897
Thermal energy from natural gas [Net calorific value]	MJ	6149.219
Outputs		
Products		
Aluminium extrusion profile [Metal products]	kg	1000
Waste for Recovery		
Aluminium scrap [Waste for recovery]	kg	289.876
Dross [Waste for recovery]	kg	0.2944
Used waste oil [Waste for recovery]	kg	0.29
Other metal scrap [Waste for recovery]	kg	1.27
Waste for Disposal		
Hazardous waste (unspec.) [Hazardous waste]	kg	1.9732
Non-hazardous waste for land-filling [Waste for disposal]	kg	2.5506
Sludge [Waste for treatment]	kg	8.65
Emissions to Water		
Water (treated waste water) [Treated waste water for release]	kg	60.4949
Chemical oxygen demand (COD)	kg	0.0214
Emissions to Air		
Nitrogen dioxide [Inorganic emissions to air]	kg	0.157
Sulphur dioxide [Inorganic emissions to air]	kg	0.0071
VOC (unspecified) [Organic emissions to air (group VOC)]	kg	0.2831

5.3.1.2 Flat-Rolling (Excluding Aluminum Foil Production)

The aluminum flat-rolling processes can be divided into two separate unit operations: hot-rolling and cold rolling. The processes may begin with direct chill cast ingot or with continuous cast coils. However, due to the fact that most aluminum hot-rolling facilities in North America include operations in which primary aluminum and secondary aluminum (or scrap) are melted (often together) and cast into large ingots which are subsequently rolled, we expand our system of the unit processes to include the metal/scrap re-melting and casting steps to avoid allocation.

5.3.1.2.1 Metal/Scrap Re-melt and Hot-Rolling

5.3.1.2.1.1 Unit Process Description

Aluminum enters a typical rolling facility in North America in four potential forms:

- aluminum scrap;
- aluminum blocks (blocks can be primary aluminum, often referred to as sow, or secondary aluminum and are cast into smaller blocks intended to be re-melted);
- molten aluminum; or
- pre-cast full size aluminum ingot

The first two forms are melted and cast into full size ingots. The third type, molten metal, can be added to the first two forms prior to casting or be used in the continuous casting process described shortly hereafter. The fourth type is typically cast at a smelting operation and delivered to a rolling facility ready to be rolled.

In the case of large integrated facilities, it often starts with molten aluminum metal produced by the previous metal production processes which is then casted and rolled.

Aluminum Scrap Aluminum Sow Rolling Ingot

Figure 29: Metal source of a rolling facility.

The process of metal/scrap melting is the same as it is described in the secondary aluminum production process: processed scrap and aluminum ingots are melted into molten metal and the molten metal is fluxed, de-gassed, treated, alloying specification adjusted, and filtered. Additional trace additives such as titanium di-boride or titanium carbide might be added to refine aluminum grains and disperse stresses. The molten aluminum is then poured into molds and cast into rolling ingots/slabs for hot and cold rolling. The ingots are typically 18 to 30 inches thick and with a weight of 15 to 30 tons.

There is an alternative approach in rolling facilities in which aluminum sheet and plate can be directly produced by a method called Continuous Casting. Continuous casting takes molten metal and solidifies it into a continuous strip. A variety of methods are used to solidify the metal including roll casters, belt casters and block casters. The common feature for all of these methods is that sheet is taken directly from molten metal, solidified and coiled in one operation. Currently about 20% of the North American sheet and plate production is produced by continuous casting. It is worthwhile to note that continuous casting products can be either directly used for end-use purpose, or further rolled to produce thinner gauge products.

Direct chill cast aluminum ingots/slabs or continuous cast strips, while still hot, can be further treated and hot rolled. Or in other cases, completely chilled ingots or strips can be used for hot rolling but preheating must be done to heat the intermediates to a required temperature.

The purpose of rolling process is to produce aluminum sheet and plate with the accurate dimensions, the precise thickness and flatness, the specified mechanical properties, and the required edge quality and surface finish.

Hot rolling is the method of rolling metal at a temperature high enough to avoid strain-hardening (work-hardening) as the metal is deformed. The ingots are preheated to about 1000 F and fed through a hot reversing mill. In the reversing mill, the coil passes back and forth between rolls and the thickness is reduced to 4 to 5 inches with a corresponding increase in length. This part of the hot rolling process is also called a Breakdown rolling process.

Following the reversing mills, the slabs are fed to a continuous hot mill where the thickness is further reduced to as thin as 1/10 inch in thickness. The metal, called re-roll or hot band, is edge trimmed and rolled into a coil and is ready to be transferred to the cold mill.

During the hot rolling process, both breakdown and continuous rolling, lubricant is used both to prevent the metal from sticking to rolls and to constantly cool down the metal to its desired rolling temperature. The rolling process itself generates additional heat due to friction between metal and the rolls and the metal's internal friction. The lubricant/coolant is an emulsion of water with about 5 percent oil and it is applied by spraying on the rolls through installed nozzles. It is also continuously filtered and recirculated (AA, 1998; AA, 2007 etc.).

In summary, this unit process (as defined for this LCA study) begins with the shipment of process materials to their storage areas on-site. The operations associated with this process include:

- Shipment and handling of primary and secondary ingots, processed (clean) scraps and other ancillary materials;
- Melting of ingots and scraps, refining, purification, alloying, and treatment of molten metal;
- Casting operations;
- Breakdown hot rolling of cast slabs and rolling ingots;
- Continuous hot rolling;
- Edge trimming, finishing, coiling and packaging;
- Recovery and handling of internal process scrap;
- Maintenance and repair of plant and equipment; and
- Treatment of process air, liquids, and solids.

The output of this unit process is hot rolled coil (re-roll coil), sheet and plate, or intermediate rolling products (continuous casting products) transported to an end-use customer or to a cold rolling and finishing facility.

5.3.1.2.1.2 Source of Raw Material and Energy

The source of major raw materials for this unit process is the processed aluminum scrap and primary and secondary aluminum ingots. Many facilities process un-treated scrap on site, while others purchase processed scrap from specialized scrap processers. Similar to the extrusion operations described in the previous section, all ingots and scraps are assumed to be domestically sourced from the North American region.

The source of auxiliary materials is also assumed to be mostly domestic and/or local.

Almost all rolling facilities in North America use natural gas and electric power as the primary sources of energy. Electric furnaces use electric power as their major energy source. Unlike primary aluminum producers, most rolling facilities in North America do not purchase electricity from specific power generators, nor do they own any power generators. In stead, they purchase their power from local utility companies.

Based on our survey results, hot-rolled aluminum products made in North America contains a considerable proportion of metal recycled from aluminum scrap. The metal composition of products, based on metal feedstock information collected at the melting furnaces for rolling ingot production or subsequent rolling on-site, is shown in **Table 33**.

Table 33: Metal composition of hot-rolled aluminum products in North America

Category of Metal Source	Percentage
Primary Metal (including alloy agents)	32.5

Recovered Metal from Internal Process (Run-Around) Scrap	4.0
Recovered Metal from Other Post-Industrial Scrap	24.9
Recovered Metal from Post-Consumer Scrap	38.6

Note:

- *This information is based on reports from individual facilities regarding to the metal feedstock at melting furnaces for rolling ingot making;*
- *The information represents the production of 2.9 million metric tons of hot-rolled products;*
- *The percentage is given as a weighted average based on production volumes of each facility;*
- *Assumptions were made to calculate the results due to the fact that the recycled ingots used for remelting were purchased from independent recyclers, and that although in small amount, the exact source of metal of a category of reported aluminum ingots could not be identified;*
- *Definitions of Internal Process (Run-Around) Scrap, Post-Industrial Scrap and Post-Consumer Scrap are consistent with ISO 14021/25 (2006) on environmental labels and declarations, and the related interpretations by UL Environment;*
- *Products shipped to different market sectors may vary significantly on its metal compositions;*
- *Due to the involvement of assumptions for the calculations, this information can only be deemed as the best estimates from the industry.*

5.3.1.2.1.3 Unit Process Inputs and Outputs

Inputs and outputs of this unit process are shown in **Table 34**.

Table 34: Inputs and outputs of the remelting and hot rolling process, representing the production of 1000 kg of hot rolled products

Flow	Unit	Amount
Inputs		
Materials		
Aluminium ingot (primary) [Metals]	kg	331.6
Aluminium scrap or ingot (secondary) [Metals]	kg	706.9
Miscellaneous alloy elements [Operating materials]	kg	8.1
Argon [Operating materials]	kg	0.4284
Chlorine [Operating materials]	kg	0.02
Nitrogen [Operating materials]	kg	2.62
Cryolite [Operating materials]	kg	0.0016
Potassium chloride [Operating materials]	kg	1.4756
Sodium chloride (salt) [Operating materials]	kg	1.9858

Hydraulic oil [Operating materials]	kg	0.1811
Lubricant (unspecified oil) [Operating materials]	kg	0.0494
Filter media [Operating materials]	kg	1.0502
Quicklime [Operating materials]	kg	0.2001
Refractory [Operating materials]	kg	0.4454
Caustic soda (100%) [Operating materials]	kg	0.0105
Sulphuric acid (96%) [Operating materials]	kg	0.1076
Steel packaging [Packaging materials]	kg	0.0108
Water (fresh water) [Operating materials]	kg	175.818
Energy		
Electricity [Electric power]	kWh	113.424
Thermal energy from natural gas [Net calorific value]	MJ	3812.315
Outputs		
Products		
Aluminium coil, or sheet and plate [Products]	kg	1000
Waste for Recovery		
Aluminium scrap [Waste for recovery]	kg	3.605
Dross [Waste for recovery]	kg	39.21
Saltcake [Waste for recovery]	kg	4.1033
Used oil [Waste for recovery]	kg	0.839
Miscellaneous metal scrap [Waste for recovery]	kg	1.43
Waste for Disposal		
Filter dust [Waste]	kg	0.6743
Non-hazardous waste for land-filling [Waste for disposal]	kg	0.64
Refractory [Waste for disposal]	kg	0.9104
Solid waste [Hazardous waste for disposal]	kg	1.2
Emissions to Water		
Water (treated waste water) [Treated waste water for release]	kg	93.7428
Aluminium (+III) [Inorganic emissions to fresh water]	kg	7.27E-05
Chemical oxygen demand (COD)	kg	0.019
Biological oxygen demand (BOD)	kg	0.0051
Heavy metals to water (unspecified)	kg	0.0033
Phosphorus [Inorganic emissions to fresh water]	kg	2.50E-05
Emissions to Air		
Chlorine [Inorganic emissions to air]	kg	0.00057
Dust [Particles to air]	kg	0.1216
Hydrogen chloride [Inorganic emissions to air]	kg	0.0575
Hydrogen fluoride [Inorganic emissions to air]	kg	0.0011
Lead (+II) [Heavy metals to air]	kg	3.91E-05
Methane [Organic emissions to air (group VOC)]	kg	0.0029
Nitrogen dioxide [Inorganic emissions to air]	kg	0.2262
Nitrous oxide (laughing gas) [Inorganic emissions to air]	kg	0.0017

Sulphur dioxide [Inorganic emissions to air]	kg	0.0082
VOC (unspecified) [Organic emissions to air (group VOC)]	kg	0.2889
Water vapour [Inorganic emissions to air]	kg	82.3

5.3.1.2.2 Cold-Rolling

5.3.1.2.2.1 Unit Process Description

Cold rolling is the rolling of the metal at a temperature low enough for strain-hardening (work-hardening) to occur, even if the metal would feel hot to human senses.

The purpose of cold rolling is to give aluminum sheet a desired strength and temper; or to provide a final surface finish; or to reduce the sheet to very small thicknesses. For example, aluminum beverage can stock is cold-rolled from sheet about one-tenth of an inch thick down to about one-hundredth of an inch. This may be done in three or four passes through a single-stand mill or in one pass through a multiple-stand mill.

Prior to the cold mill, the coils may be annealed to give the metal the workability for down-stream working. The coils are then passed through multiple sets of rolls to reduce the gauge. The resulted coils are cut to the width and length as required by customers. The coils are packaged to prevent damage to the metal in shipping.

Although aluminum sheet enters the cold rolling mill “cold” at room temperature, the friction and pressure of rolling may raise its temperature to about 180 F (80 C) or more. This excess heat must be removed by an appropriate coolant/lubricant.

Lubricants used for cold rolling are usually composed of a load bearing additive in a light petroleum distillate oil. Oil-water emulsions have been developed for high speed cold rolling and have been adopted at some mills. Rolling lubricants are filtered to remove rolling wear debris and then recirculated (AA, 1998; AA, 2007 etc.).

In Summary, this unit process (as defined for this LCA study) begins with the shipment of process materials to their storage areas on-site. The operations associated with this process include:

- Shipment and handling of intermediate rolling products (re-roll coil or continuous casting products);
- Continuous cold rolling;
- Cutting and trimming;
- Finishing and packaging;
- Recovery and handling of internal process scrap and by-products of beneficial use;
- Maintenance and repair of plant and equipment; and
- Treatment of process air, liquids, and solids.

The output of this unit process is semi-fabricated or finished aluminum sheet and plate products transported to an intermediate or end user.

5.3.1.2.2.2 Source of Raw Materials and Energy

The source of major raw material is the re-roll coils or continuous cast coils/sheets from the previous hot rolling process. They could be produced from the same facility or from a different facility.

The source of auxiliary materials is also assumed to be mostly domestic and/or local.

The metal composition is calculated by taking into consideration of the hot-rolled coil production reported at the previous unit process, and the characteristics of individual facilities in their capability of recycling internally generated process scraps. The result is shown in **Table 35**.

Table 35: Metal composition of cold-rolled aluminum products in North America

Category of Metal Source	Percentage
Primary Metal (including alloying elements)	32.5
Recovered Metal from Internal Process (Run-Around) Scrap	18.5
Recovered Metal from Other Post-Industrial Scrap	10.4
Recovered Metal from Post-Consumer Scrap	38.6

Note:

- *This information is based on reports from individual facilities regarding to the metal feedstock at melting furnaces for rolling ingot making;*
- *The information represents 2.92 million metric tons of reported production, or 85 percent of the industry's total producer shipment in 2010;*
- *The percentage is given as a weighted average based on production volumes of each facility;*
- *Assumptions were made to calculate the results due to the fact that the recycled ingots used for remelting were purchased from independent recyclers, and that although in small amount, the exact source of metal of a category of reported aluminum ingots could not be identified;*
- *Definitions of Internal Process (Run-Around) Scrap, Post-Industrial Scrap and Post-Consumer Scrap are consistent with ISO 14021/25 (2006) on environmental labels and declarations, and the related interpretations by UL Environment;*
- *Products shipped to different market sectors may vary significantly on its metal compositions;*
- *Due to the involvement of assumptions for the calculations, this information can only be deemed as the best estimates from the industry.*

5.3.1.2.2.3 Unit Process Inputs and Outputs

The inputs and outputs of the cold rolling process are shown in **Table 36**.

Table 36: Inputs and outputs of the cold rolling process, representing the production of 1000 kg cold rolled products

Flow	Unit	Amount
Inputs		
Materials		
Aluminium coil or strip (for rolling) [Resources, metals]	kg	1244.718
Nitrogen gas [Inorganic operating materials]	kg	0.6508
Emulsifier (in 100% oil) [Operating materials]	kg	0.5381
Filter media [Operating materials]	kg	0.4608
Hydraulic oil [Operating materials]	kg	0.54
Lubricant (in 100% oil) [Operating materials]	kg	1.37
Chromium [Operating materials]	kg	0.0027
Paint (surface coating paint) [Operating materials]	kg	2.403
Quicklime [Minerals, operating materials]	kg	0.3235
Sodium hydroxide (100%) [Inorganic operating materials]	kg	0.0538
Solvent [Operating materials]	kg	0.4089
Sulphuric acid (96%) [Inorganic operating materials]	kg	3.9063
Water (fresh water) [Water, operating materials]	kg	488.4201
Wax synthetic [Organic operating materials]	kg	0.0199
Chemicals (unspecified) [Operating materials]	kg	0.0327
Cardboard (packaging) [Packaging materials]	kg	18.2052
Paper packaging [Packaging materials]	kg	0.9494
Plastic packaging [Packaging materials]	kg	2.1935
Steel packaging [Packaging materials]	kg	0.1765
Wood packaging [Packaging materials]	kg	8.9026
Energy		
Electricity [Electric power]	kWh	366.202
Thermal energy from natural gas [Net calorific value]	MJ	2196.06
Outputs		
Products		
Aluminium parts or coils (cold rolled) [Products]	kg	1000
Waste for Recovery		
Aluminium scrap [Waste for recovery]	kg	244.7
Coco/Latex Filter cake [Waste for recovery]	kg	0.3198
Paper (unspecified) [Waste for recovery]	kg	0.0006
Used oil (with water, to treatment) [Waste for recovery]	kg	0.3786
Wood (raw material) [Waste for recovery]	kg	0.0057

Waste for Disposal		
Filter dust [waste]	kg	0.0249
Hazardous waste (unspec.) [Hazardous waste]	kg	0.24
Non-hazardous waste for land-filling [Waste for disposal]	kg	1.95
Emissions to Water		
Water (treated waste water) [Treated waste water for release]	kg	216.0161
Aluminium (+III) [Inorganic emissions to fresh water]	kg	0.0001
Biological oxygen demand (BOD) [Analytical measures to fresh water]	kg	0.0004
Chemical oxygen demand (COD) [Analytical measures to fresh water]	kg	0.0091
Heavy metals to water (unspecified) [Heavy metals to fresh water]	kg	0.0001
Suspended solids, unspecified [Particles to fresh water]	kg	0.0166
Zinc (+II) [Heavy metals to fresh water]	kg	0.0001
Emissions to Air		
Ammonia [Inorganic emissions to air]	kg	7.12E-05
Carbon monoxide [Inorganic emissions to air]	kg	0.0041
Dust (PM10) [Particles to air]	kg	0.0663
Heavy metals to air (unspecified) [Heavy metals to air]	kg	0.0001
Lead (+II) [Heavy metals to air]	kg	1.10E-06
Methane [Organic emissions to air (group VOC)]	kg	0.0012
Nitrogen dioxide [Inorganic emissions to air]	kg	0.061
Nitrous oxide (laughing gas) [Inorganic emissions to air]	kg	0.0011
Sulphur dioxide [Inorganic emissions to air]	kg	0.0003
VOC (unspecified) [Organic emissions to air (group VOC)]	kg	0.2648
Water vapour [Inorganic emissions to the air]	kg	272

5.3.1.3 Shape Casting

Aluminum shape casting, also called aluminum foundry, is an operation process very similar to primary and secondary ingot casting, in which molten metal is poured or injected into a mold and the metal is solidified to form a shape. The difference is that the purpose of shape casting is to produce a final product to be used for its designated functionality, while the process of ingot casting is to produce an intermediate product to be further processed for end use.

Most aluminum cast shapes are produced from post-consumer and pre-consumer aluminum scraps. Aluminum foundries are designed to process a range of old and new scrap qualities that contain alloying elements. In 2010, cast aluminum product shipment was 1.75 million metric tons in North America.

Aluminum cast shapes can be used in any industries including transportation, building and construction, machinery and equipment, and consumer durables. **Figure 30** shows the US aluminum casting shipments by major markets.

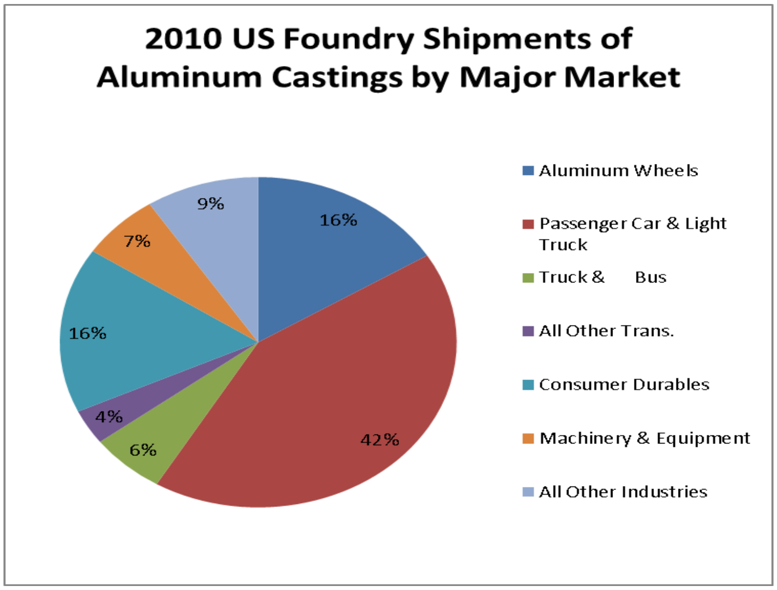

Figure 30: 2010 shipments of shape casted aluminum products

5.3.1.3.1 Survey Failure and the Source of Data

For the purpose of this study, the Aluminum Association had initially identified approximately 50 aluminum foundry companies in the North American region as its data survey target and subsequently sent survey forms to these companies. None of them are members of the Aluminum Association.

As a result, none of the companies responded the survey. A renewed effort was followed by the Association by commissioning a professional industrial data survey service provider to work on the task. This effort ended up collecting very limited data and information from two dozen small facilities. However, the data and information collected was in low quality and the accumulated production output of the survey responders only represents 0.5% of the aluminum foundry industry's total output.

For this reason, the Association decided to abandon the collected data and information and seek for alternative solutions.

Consequently, a limited-scope survey on metal feedstock was conducted to several large facilities to figure out the proportions of primary metal and scrap or secondary metal used in those facilities. For all other necessary quantitative input and output information related to aluminum shape casting, available data from the GaBi database was used to model the unit production process.

5.3.1.3.2 Unit Process Description

There are three main aluminum shape casting technologies: die casting, permanent mold casting, and sand casting. The technology employed is dependent on the shapes produced and employs both permanent and non-permanent molds.

Of the 1.75 million metric tons of products shipped in 2010, the share of die casting, permanent mold casting and sand casting was approximately 60%, 30% and 9%, respectively.

Die casting is “a repetitive operation wherein identical parts are cast at maximum production rates by forcing molten metal under considerable pressure into dies, which are precision made in two (or more) parts called cavity halves” (AFS, 1993).

Die halves are mounted onto die casting machine and are held tight to withstand high pressure. Molten metal is injected into the die where it chills rapidly. When the metal is solidified, the die is opened and the hot casting is ejected. The die is then closed again and the casting cycle is repeated.

Following the ejection of castings, trimming, polishing, drilling, tapping, and other subsequent finishing operations are performed depending on the requirement of individual products. The products may also be painted and coated depending on the end-use requirement.

Die casting technology is capable of producing identical products in great quantities. However, it is in disadvantage position compared with the other two technologies in producing very complex shapes.

Permanent mold casting is the process of “pouring molten metal into permanent metal molds using gravity, low pressure, vacuum, centrifugal pressure or tilt pouring” (AFS, 1993). The metal molds usually are made of high-alloy iron or steel and have a production life of 10,000 to 120,000 or more castings.

Sand casting is the process of aluminum casting in which the molds and cores are made of sand. Sand grains are bonded together to make molds and cores by the means of natural clay and water binding, or by chemical binding. The molds and cores can be made either manually or mechanically, with automated systems and operations. The casting itself can also be done by automated systems and operations.

“Sand casting is the simplest and most versatile of the processes used to cast aluminum. Sand molds generally are quite easy to make and relatively simple to change or modify if it’s required” (AFS, 1993). Sand casting can be used to make very high quality products, either in simple forms, or very complex shapes such as automotive engines and aerospace parts.

In Summary, the common operations involved in shape casting (as defined for this LCA study) begins with the shipment of materials to the site and the preparation of cores and molds. The operations associated with this process include:

- Shipment of raw materials;
- Preparation and forming of cores and molds;
- Melting of scraps and metals
- Alloying, treating and handling of molten metal;
- Casting operations (pouring or injecting metal into molds);
- Homogenizing and cooling;
- Surface treatment and finishing, including coating and painting;
- Packaging;
- Recovery and handling of internal process scrap and dross;
- Recovery and handling of other by-products of beneficial use;
- Maintenance and repair of plant and equipment; and
- Treatment of process air, liquids, and solids.

The output of this unit process is cast aluminum components that are transported to a component or final product manufacturer.

5.3.1.3.3 Source of Raw Materials and Energy

The source of major raw materials for this unit process is the processed aluminum scrap and primary and secondary aluminum ingots. Some facilities process un-treated scrap on site, while others purchase processed scrap from specialized scrap processers. Similar to the other semi-fabrication operations, all ingots and scraps are assumed to be domestically sourced from the North American region.

The source of auxiliary materials is also assumed to be mostly domestic and/or local.

It is assumed that, like most of the other secondary aluminum production and aluminum semi-fabrication facilities, the aluminum foundry facilities in North America use natural gas and electric power as the primary sources of energy. Natural gas is the cleanest and the most efficient available fossil fuel energy source for aluminum melting. Electric furnaces use electric power as their major energy source. Similarly, it is assumed that unlike primary aluminum producers, most shape casting facilities in North America do not purchase electricity from specific power generators, nor do they own any power generators. In stead, they purchase their power from local utility companies.

Based on our limited-scope metal feedstock survey, on average, aluminum foundry facilities in North America use **15 percent** of primary metal and **85 percent** of scrap or secondary metal to produce cast products.

5.3.1.3.4 Unit Process Inputs and Outputs

Table 37 shows the input and output information of this unit process.

Table 37: Inputs and outputs of aluminum shape casting process (die casting only), representing the production of 1000 cast products. Original data source:

Flow	Unit	Amount
Inputs		
Materials		
Aluminium ingot (primary) [Metals]	kg	156.75
Aluminium ingot (scrap or secondary) [Metals]	kg	888.25
Energy		
Electricity [Electric power]	kWh	970
Thermal energy from natural gas [Net calorific value]	MJ	1900
Outputs		
Products		
Aluminium casting parts or products [Metal products]	kg	1000
Waste for Recovery		
Aluminium scrap [Waste for recovery]	kg	45
Emissions to Air		
Dust (PM2,5 - PM10) [Particles to air]	kg	0.3

5.3.2 LCI Results of Semi-Fabrications

This section presents the LCI results of semi-fabricated aluminum products in the North America region.

The "cradle-to-gate" LCI is represented by selected inventory parameters. The results are based on the actual mix of primary and secondary aluminium being input into North American extruders, casters and rolling mills in year 2010. The models used to calculate the LCI are shown in **Figure 31**, **Figure 32**, **Figure 33**, and **Figure 34**.

In addition, two of the most interesting LCI parameters – primary energy demand and CO_2 emissions – are also presented in the "gate-to-gate" format for users with different applications.

The results are shown in **Table 38** and **Table 39**, respectively.

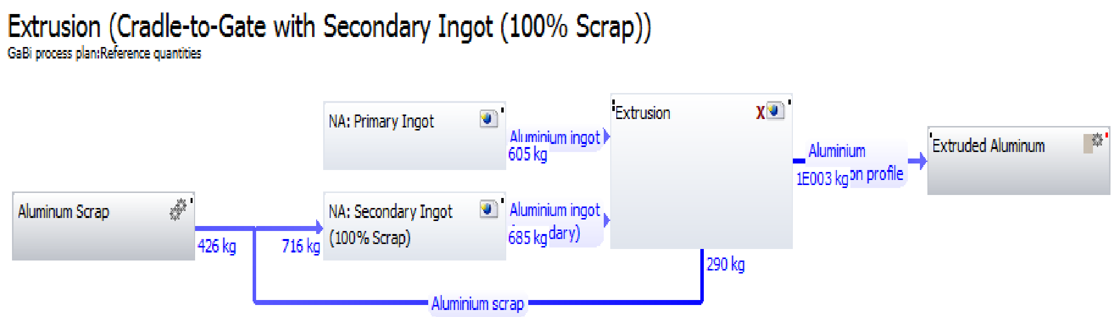

Figure 31: Illustration of the cradle-to-gate model for aluminum extrusion, representing 1000 kg of aluminum extrusion products.

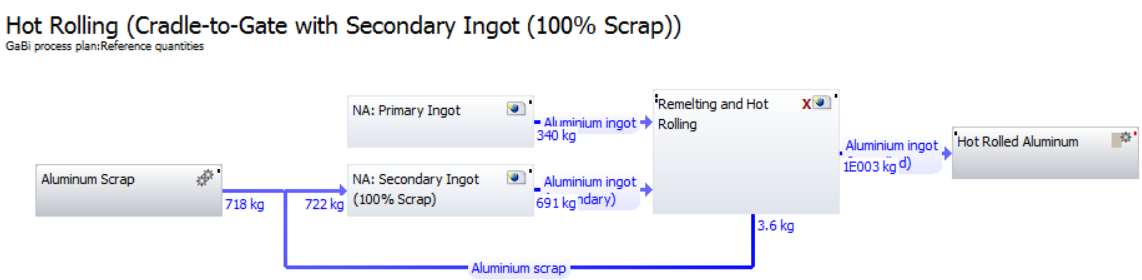

Figure 32: Illustration of the cradle-to-gate model for aluminum hot-rolling, representing 1000 kg of aluminum hot-rolled products.

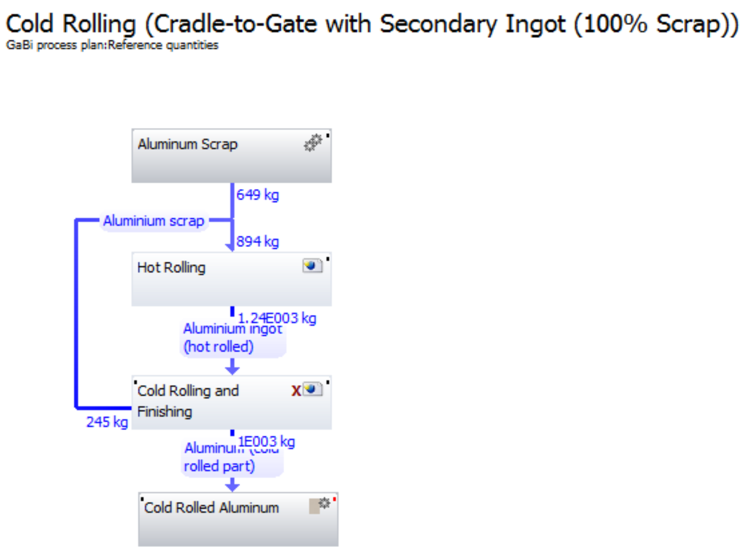

Figure 33: Illustration of the cradle-to-gate model for aluminum cold-rolling, representing 1000 kg of aluminum cold-rolled products.

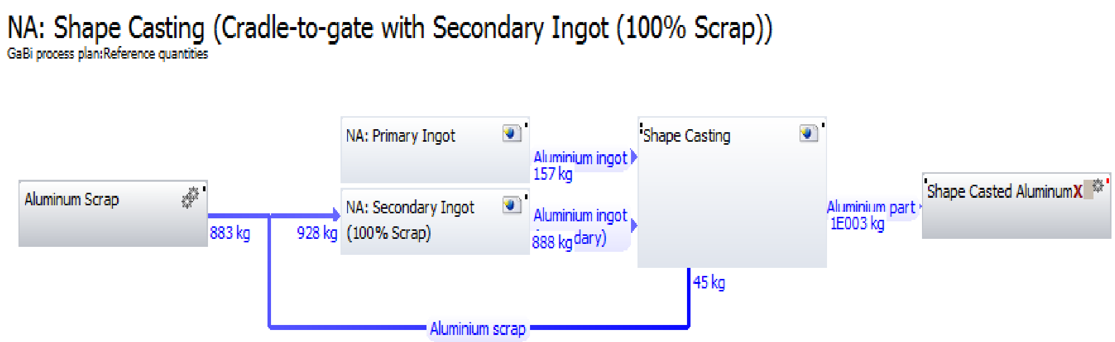

Figure 34: Illustration of the cradle-to-gate model for aluminum shape casting, representing 1000 kg of aluminum cast products

Table 38: Cradle-to-gate LCI results of aluminum semi-fabrications, in selected parameters and representing 1000 kg of fabricated products

Inventory Category	Extruded Aluminum	Hot Rolled Aluminum	Cold Rolled Aluminum	Cast Aluminum
Energy (MJ)				
Non-renewable energy	7.13E+04	4.36E+04	6.13E+04	3.43E+04
Other renewable energy	8.23E+02	3.73E+02	1.19E+03	5.82E+02
Hydroelectric energy	3.04E+04	1.77E+04	2.22E+04	8.75E+03
Resources (kg)				
Bauxite	3.80E+03	2.22E+03	2.76E+03	1.05E+03
Net Process Water	3.13E+03	2.01E+03	2.20E+03	1.07E+03
Air Emissions (kg)				
Carbon dioxide	5.85E+03	3.52E+03	4.79E+03	2.52E+03

Carbon monoxide	2.86E+00	1.41E+00	2.03E+00	8.88E-01
Chlorine	1.95E-03	2.35E-03	2.97E-03	2.14E-03
Flourine/Fluorides	3.37E-01	1.96E-01	2.44E-01	9.29E-02
Hydrogen chloride	3.61E-01	2.93E-01	3.70E-01	1.70E-01
Hydrogen fluoride	3.91E-01	2.37E-01	2.95E-01	1.26E-01
Nitrogen oxides	1.29E+01	7.18E+00	9.53E+00	4.59E+00
Nitrous oxide	8.39E-02	4.39E-02	6.21E-02	3.29E-02
Sulphur oxides	2.72E+01	1.59E+01	2.07E+01	9.75E+00
Non-methane VOCs	1.32E+00	9.36E-01	1.52E+00	4.78E-01
Methane	1.04E+01	5.92E+00	8.06E+00	4.15E+00
Dust (PM10)	1.93E-01	3.20E-01	4.65E-01	2.50E-01
Dust (PM2.5)	9.31E-01	5.43E-01	6.96E-01	3.00E-01
Water Emissions (kg)				
BOD	3.34E-02	2.18E-02	8.58E-02	1.26E-02
COD	9.92E-01	5.94E-01	1.03E+00	5.13E-01
Heavy metals	4.10E+01	2.39E+01	2.99E+01	1.18E+01
Ammonia	2.35E-03	1.06E-03	1.94E-03	1.81E-03
Flourine/Flourides	1.21E+00	7.24E-01	1.16E+00	1.01E+00
Phosphate	1.17E-03	6.74E-04	1.05E-03	4.43E-04
Waste (kg)				
Total waste	2269.115	1286.546	1612.759	655.193

Table 39: Gate-to-gate primary energy and CO_2 emission results of aluminum semi-fabrications, representing 1000 kg of fabricated products

Inventory Parameter	Unit	Aluminum Extrusions	Hot Rolling	Cold Rolling	Shape Casting
Primary Energy Demand	GJ/ton	11.36	7.06	7.92	12.15
Non renewable	GJ/ton	10.92	6.55	7.05	11.43
Renewable	GJ/ton	0.44	0.51	0.87	0.72
CO_2 emissions	ton CO_2/ ton	0.66	0.41	0.41	0.72

5.3.3 LCIA Results of Semi-Fabricated Aluminum Products

This section presents the LCIA results of semi-fabricated aluminum products in the North America region. Both “cradle-to-gate” and “cradle-to-grave” results are provided for users with different applications.

The models used to calculate the “cradle-to-grave” results are shown in **Figure 35**, **Figure 36**, **Figure 37**, and **Figure 38**.

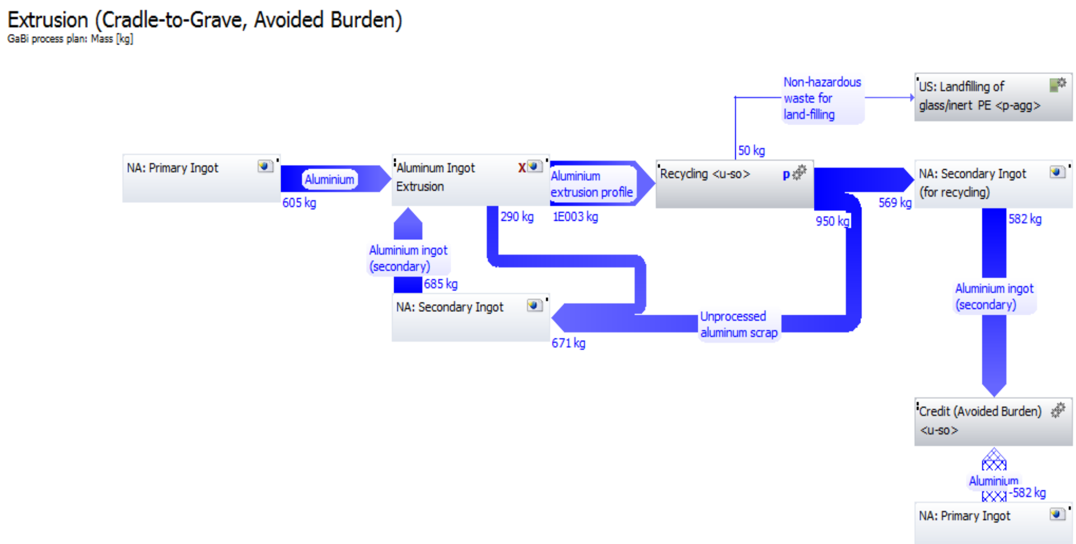

Figure 35: Illustration of the cradle-to-grave model for aluminum extrusion, representing 1000 kg of aluminum extrusion products.

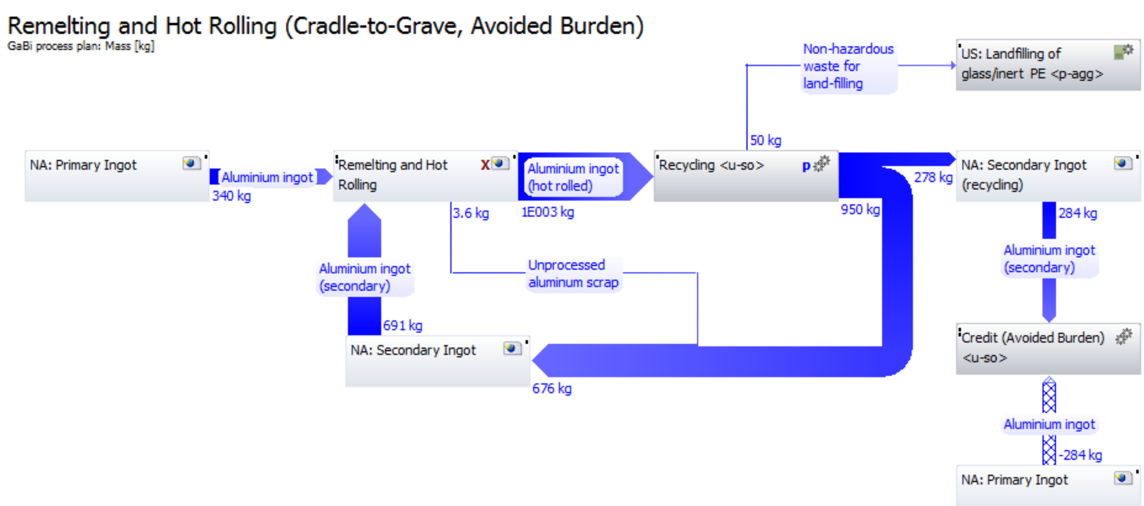

Figure 36: Illustration of the cradle-to-grave model for aluminum hot-rolling, representing 1000 kg of aluminum hot-rolled products.

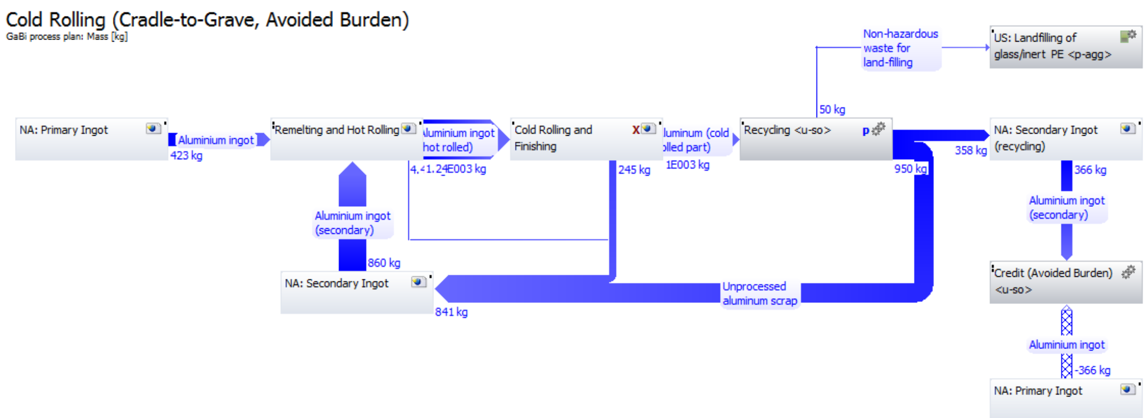

Figure 37: Illustration of the cradle-to-grave model for aluminum cold-rolling, representing 1000 kg of aluminum cold-rolled products.

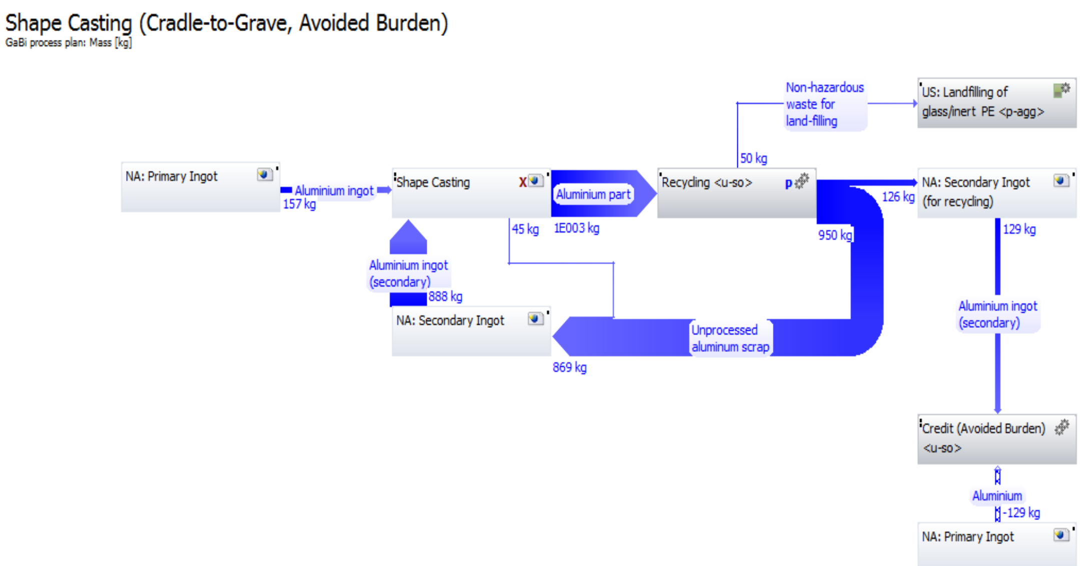

Figure 38: Illustration of the cradle-to-grave model for aluminum shape casting, representing 1000 kg of aluminum cast products.

The Cradle-to-Gate LCIA results of the examined semi-fabricated product systems are shown in **Table 40**.

Table 40: Cradle-to-gate LCIA results of semi-fabricated aluminum products, representing 1000 kg of products

Impact Assessment Category	Unit	Extrusion Products	Hot-Rolled Products	Cold-Rolled Products	Shape Cast Products
Primary Energy Demand	GJ/ton	102.44	61.81	84.86	43.65
Global Warming Potential	ton CO_2-eq/ton	6.57	3.94	5.34	2.75

Acidification Potential	kg SO_2-eq/ton	38	22	29	14
Eutrophication Potential	kg N-eq/ton	0.77	0.43	0.62	0.30
Smog Formation Potential	kg O_3-eq /ton	327	187	250	118

The Cradle-to-Grave LCIA results of the examined semi-fabricated product systems are shown in **Table 41**.

The results are based on the assumption of a 95 percent recycling rate at the end-of-life. Recycling over 95 percent is typical for aluminum products in high volume automotive and construction market sectors. Different recycling rates will end up with different results and increasing recycling can significantly reduce the potential environmental impacts of products. The cradle-to-grave results do not include the fabrication/assembly phase, nor does it include the use phase. **The use phase impact of a product, in many cases, can be much more significant than the production phase and will in fact decide the overall life cycle impact of the product itself.** Users shall take extra precautions for their purposes.

Table 41: Cradle-to-grave LCIA results of semi-fabricated aluminum products assuming 95 percent recycling rate, representing 1000 kg of products

Impact Assessment Category	Unit	Extrusion Products	Hot-Rolled Products	Cold-Rolled Products	Shape Cast Products
Primary Energy Demand	GJ/ton	28.58	27.84	40.98	27.34
Global Warming Potential	ton CO_2-eq/ton	1.76	1.73	2.48	1.69
Acidification Potential	kg SO_2-eq/ton	6	7	10	7
Eutrophication Potential	kg N-eq/ton	0.25	0.19	0.31	0.19
Smog Formation Potential	kg O_3-eq /ton	83	75	105	64

6. Conclusions and Interpretation

This study provides an update to the LCI and LCIA of the major semi-fabricated aluminum product systems manufactured in North America. The study quantifies all significant inputs and outputs of the product systems and examines the potential environmental impacts at the “cradle-to-gate” and “cradle-to-grave” levels. The “cradle-to-grave” impact is assessed through an avoided-burden, or in other terms, substitution approach.

Energy Demand Key Driver of Environmental Footprint

The study shows that **more than 60 percent** of the environmental footprints of the examined product systems are energy related. The generation of electricity, particularly from fossil fuel fired power plants, attributes to the largest share of the total footprint. The study also shows that of all the examined product systems, primary aluminum production accounts for more than 50 percent of the footprints (**Figure 39**). The semi-fabrication processes account for 11 percent, 13 percent, 22 percent, and 28 percent for extrusion, hot-rolling, cold-rolling and shape casting, respectively. Among the different unit processes of the primary aluminum production, electrolysis accounts for the largest share of footprint and most of it is due to fossil fuel fired electrical power generation at the energy supply chain.

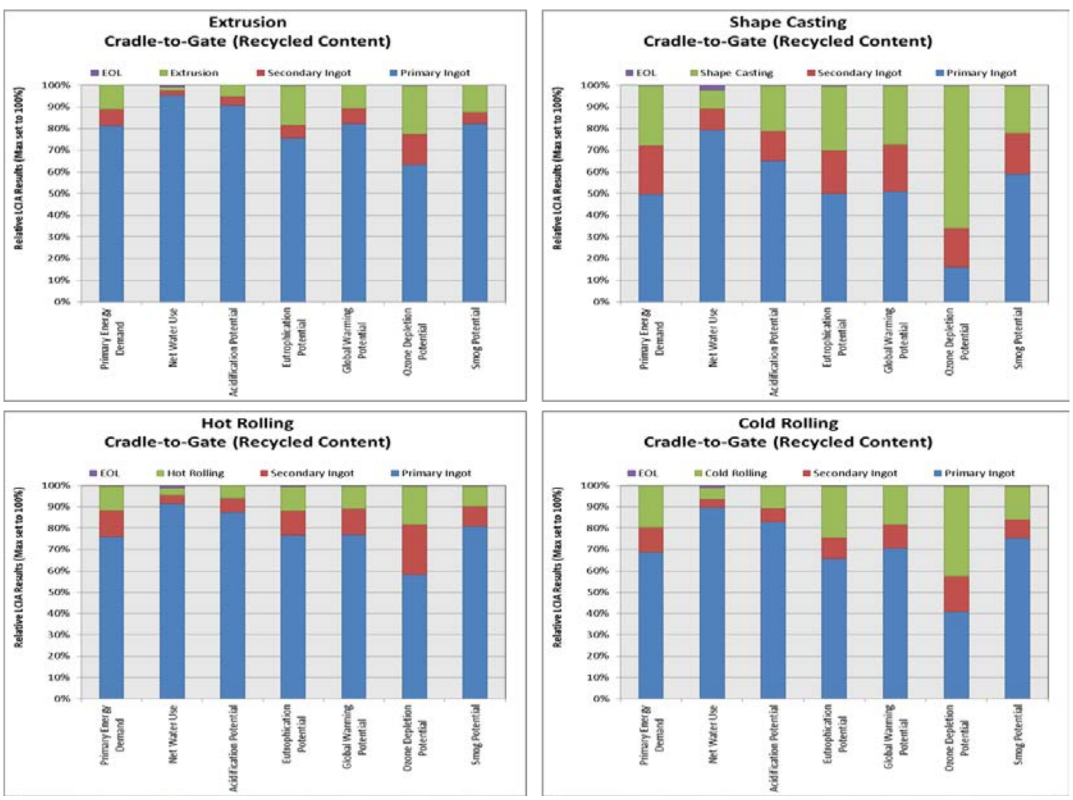

Figure 39: Breakdown of Cradle-to-Gate LCIA Results

EOL Recycling Helps Significantly Reduce Footprints

Recycling of aluminum at the end of its useful life can significantly reduce the environmental footprint and therefore the potential environmental impacts (**Figure 40**). The effect of increasing EOL recycling rates can be seen from both **Figure 41** and **Figure 42**. The figures show that **each 10 percent increase in EOL recycling can reduce the overall energy demand and global warming potential by more than 15 percent** for all examined product systems. Similar effects can also be observed regarding to other impact indicators.

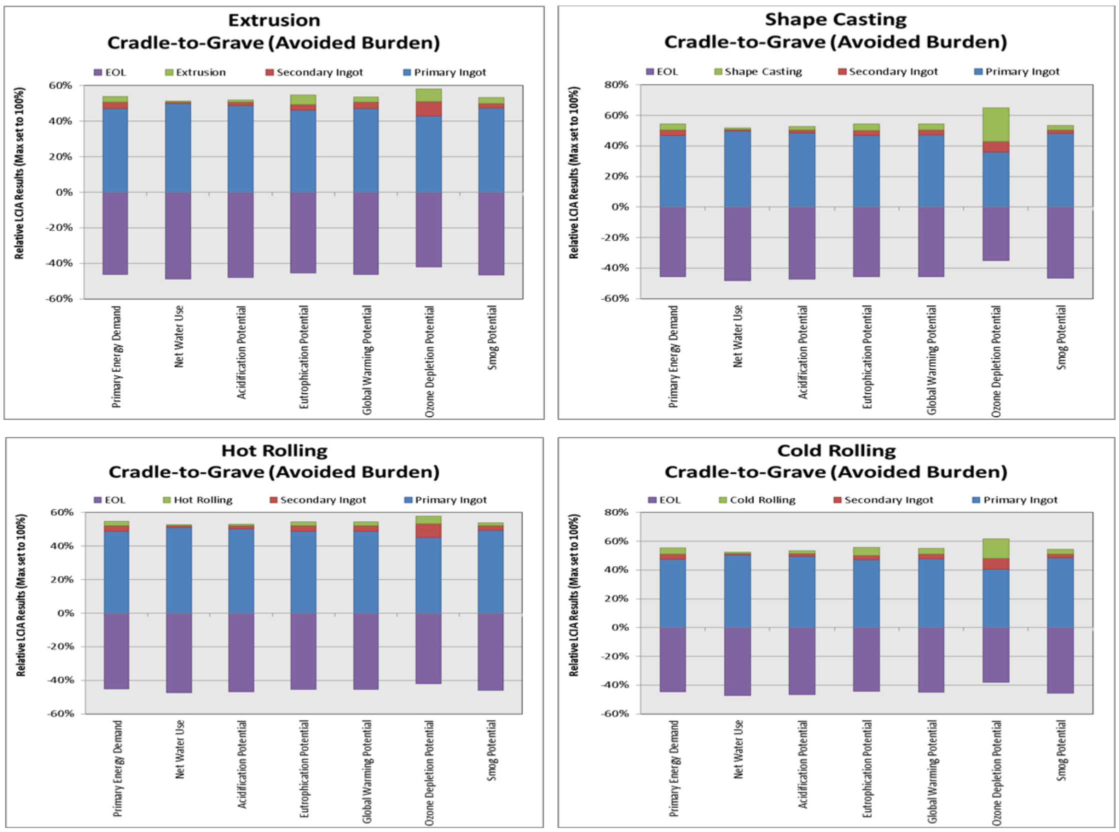

Figure 40: Breakdown of Cradle-to-Grave (excluding fabrication and use phases) LCIA results

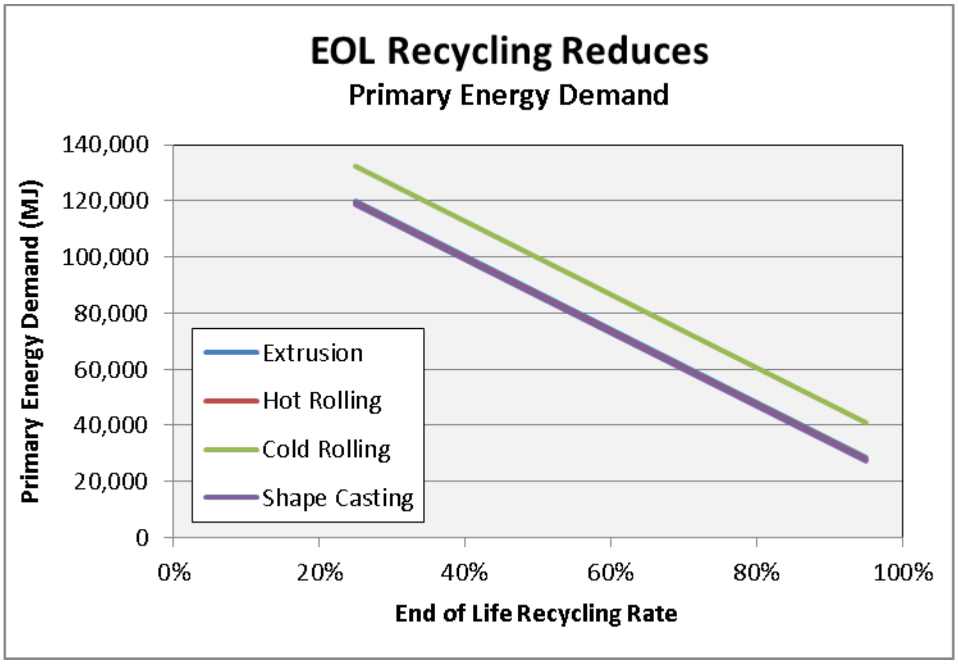

Figure 41: The impact of recycling on the overall primary energy demand of semi-fabricated aluminum products

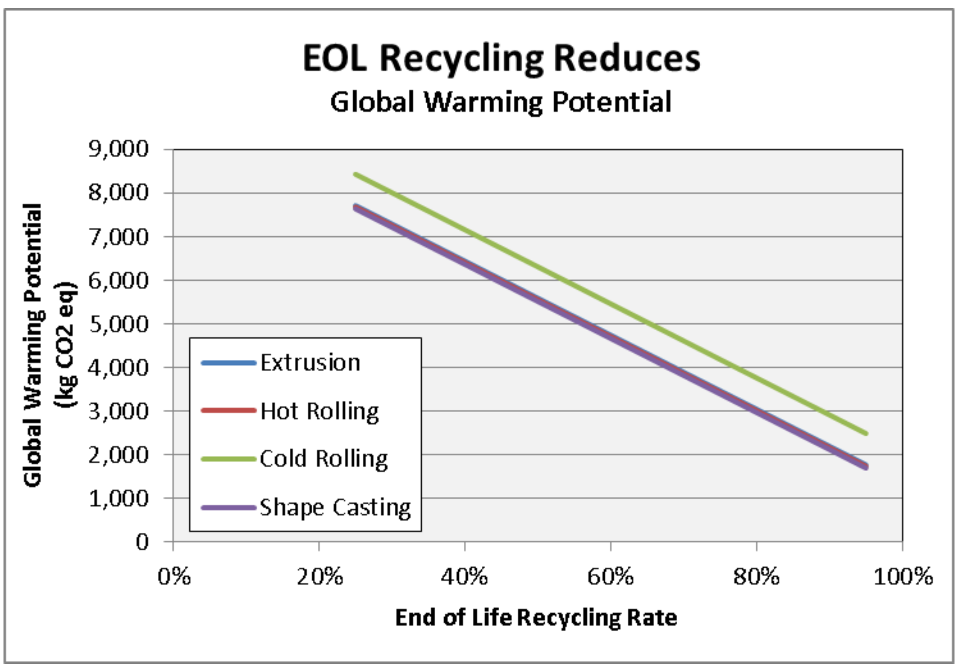

Figure 42: The impact of recycling on the overall global warming potential of semi-fabricated aluminum products

The generic environmental benefit of recycling can be quantitatively calculated by comparing the cradle-to-gate primary energy demand associated with primary metal production and the recycled metal production. **Figure 43** shows the result of such comparison. **Clearly, recycling aluminum saves 92% of energy compared to producing the metal from bauxite ore.**

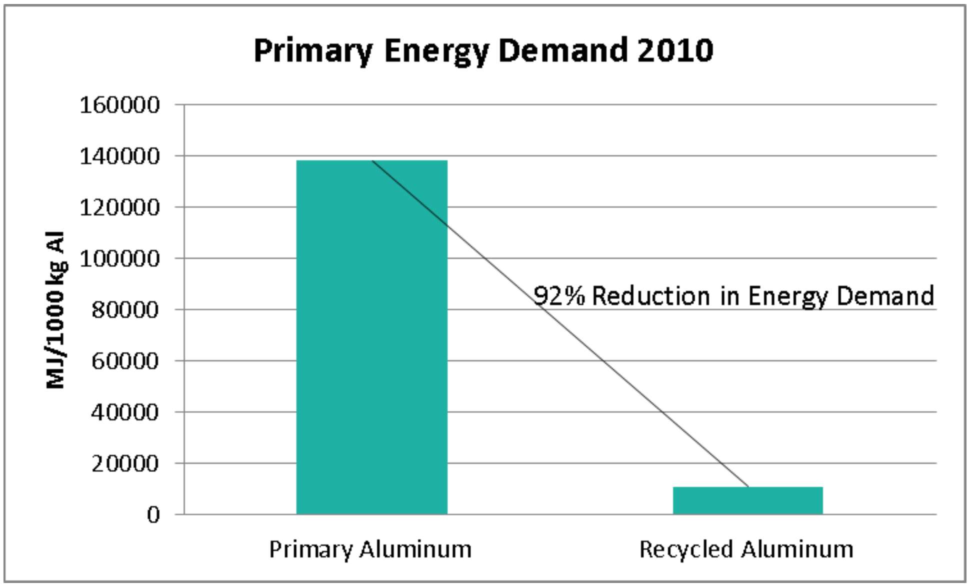

Figure 43: Energy savings of aluminum recycling in 2010

This result is slightly different from the traditionally stated **95%** energy savings. The reason for this is that the energy demand for primary aluminum production has been reduced faster than the energy demand for recycled aluminum. **Figure 44** shows the situation of the production year 1995, based on the 1998 LCI study.

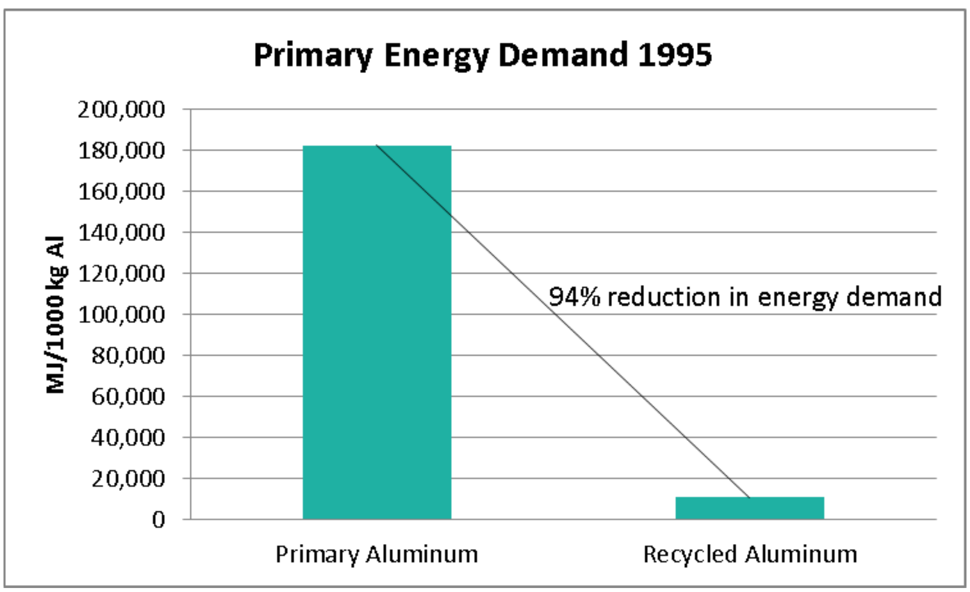

Figure 44: Energy savings of aluminum recycling in 1995

Significant Footprint Reductions Achieved

Significant progress has been made in the aluminum industry in improving energy efficiency and reducing emissions. For instance, compared to the production year of **2005**, primary energy demand and global warming potential for primary aluminum production have been reduced **11percent** and **19 percent**, respectively. And compared to the production year of **1995**, the reductions were **26 percent** and **37 percent**, respectively (**Figure 45** and **Figure 46**).

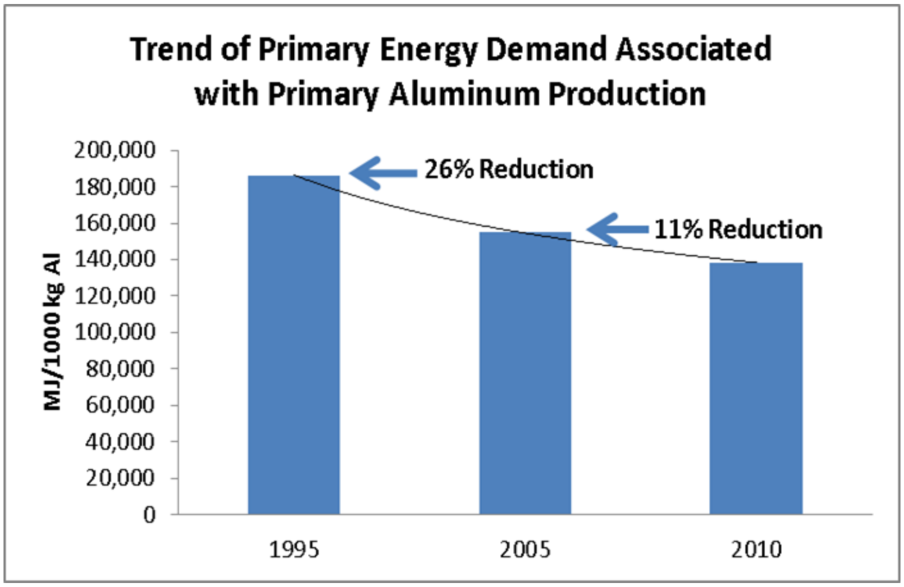

Figure 45: Trend of primary energy demand associated with primary aluminum production.

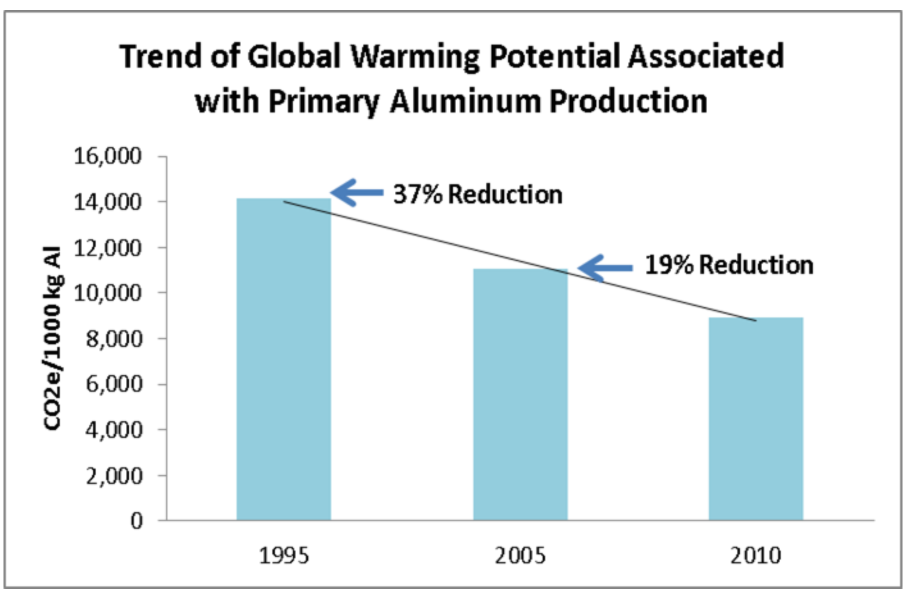

Figure 46: Trend of GWP associated with primary aluminum production.

The improvement in energy efficiency and carbon footprint for primary aluminum is partly attributed to technological progress in which computerized process control has enabled less electric power consumption during the electrolysis process and reduced emissions of greenhouse gases such as CO_2 and PFCs (**Figure 47** and **Figure 48**).

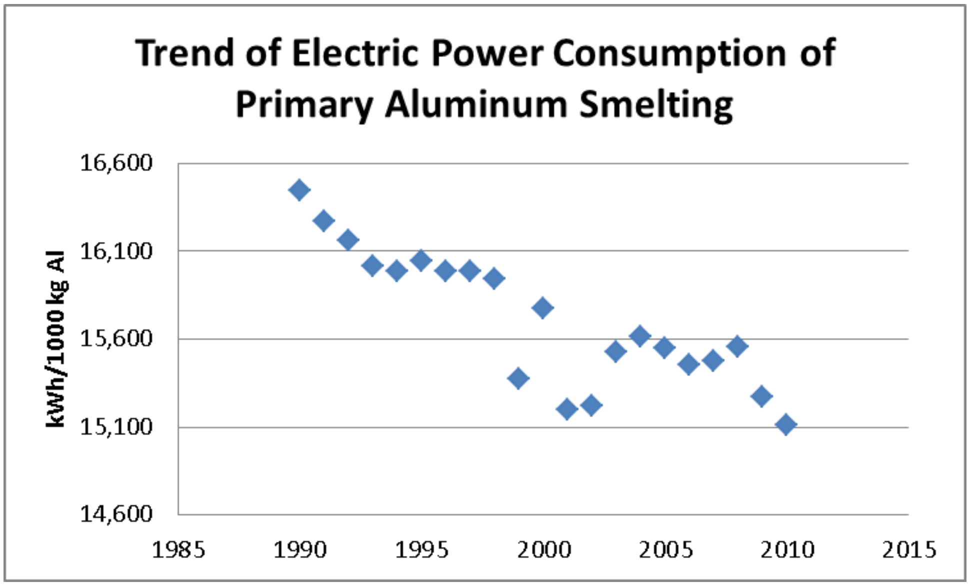

Figure 47: Trend of electric power consumption of primary aluminum smelting.

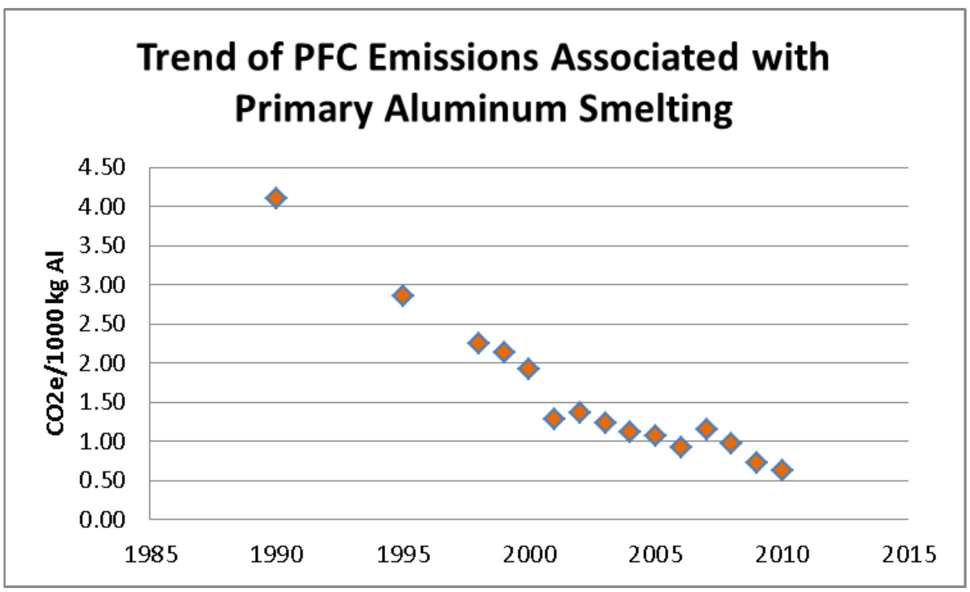

Figure 48: PFC emission intensity reductions (1990 – 2010)

The improvement in energy efficiency and carbon footprint is also attributed to the gradual phase out of old smelting technology – the Söderberg technology. Compared to the pre-bake technology, the Söderberg technology is less energy efficient and releases more emissions. During the past 20 years, the Söderberg facilities have been gradually closed and more pre-bake facilities have been built.

A third contribution factor for the improvement is the gradually increased share of renewable hydropower and decreased share of coal fired power as an energy feedstock for primary aluminum smelting (**Figure 49**). This phenomenon is essentially related in part to the phase out of Söderberg facilities which coincidentally to be facilities powered by coal fired electricity. On the other hand, most of the newly built pre-bake facilities are powered by hydro-electricity.

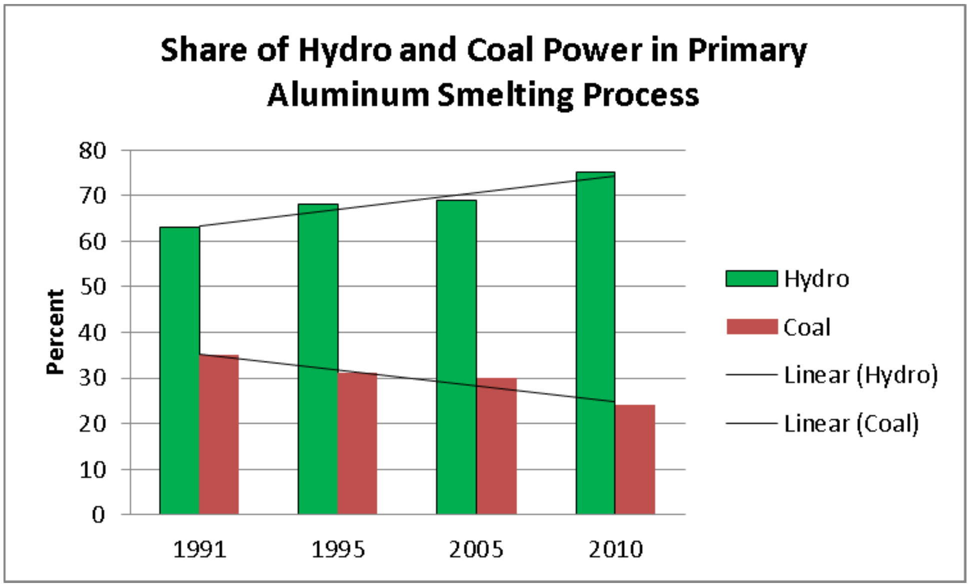

Figure 49: Relative shares of hydro power and coal fired power in primary aluminum smelting process (1990 – 2010).

Unlike the significant energy efficiency improvement achieved in primary aluminum production, the progress for aluminum recycling has been moderate. Trend in PED and related carbon footprint for aluminum recycling is showing in **Figure 50** and **Figure 51**. The production year of 2010 eventually ends up up-tick slightly.

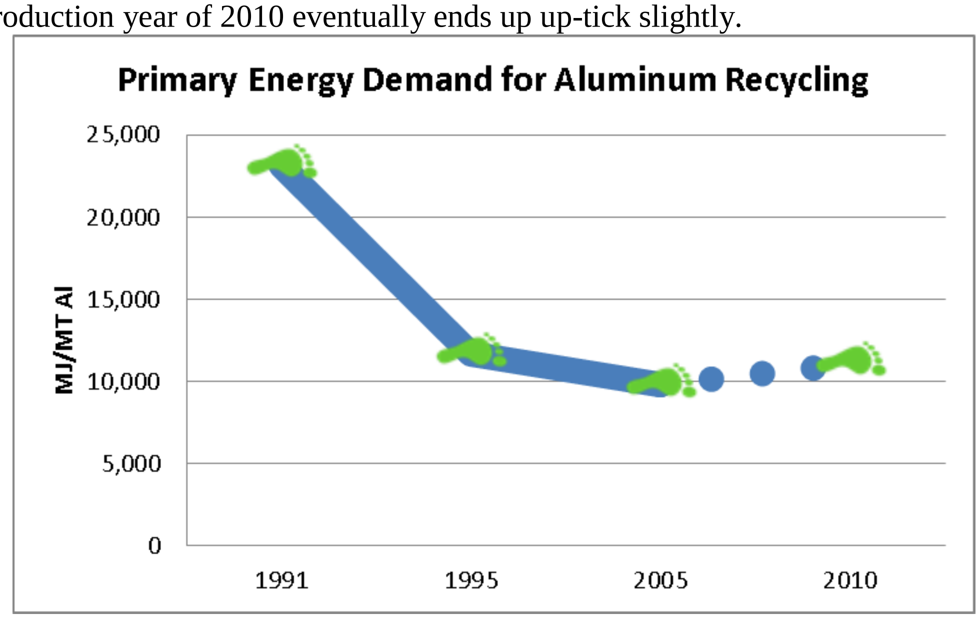

Figure 50: Trend of primary energy demand associated with aluminum recycling.

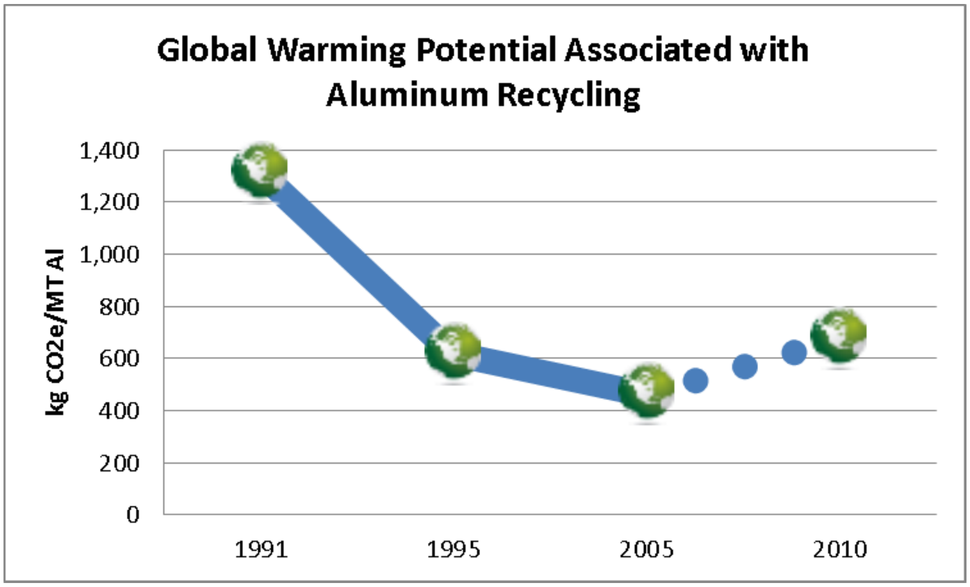

Figure 51: Trend of GWP associated with aluminum recycling.

Energy efficiency improvement for the semi-fabrication processes is more complex and mixed, with slight improvement in some case, and slight set back in other case. All improvements or set backs are within the range of statistical error. The same is true for energy related greenhouse gas emissions.

Overall, from a cradle-to-gate point of view on the examined product systems, there are significant reductions to the assessed potential environmental impacts. This is a result of both the improvement in primary metal production, and the increased use of recycled aluminum for semi-fabrications. For instance, the use of recycled aluminum in extruded and flat-rolled products was only 11 percent on average in 1995 based on the 1998 study. Under this study, however, the average content of metal from recycled source increased to more than 50 percent. The use of recycled aluminum in cast products is found to be identical for both the 1998 and this study.

Product Use Phase Another Key Consideration

It is critical to note that the use phase of products, although not included in this study, could have the biggest impact on the overall life cycle environmental footprints. Users are therefore specially cautioned to draw conclusions before including the use phase in their studies. Many LCA studies show that the environmental footprint of the production phase of a product is minimal compared to the use phase impacts. This is true across almost all market sectors including building, packaging, transportation and consumer durables. For example, the production phase of an automobile is as less as 10 percent of the total life cycle footprint and the rest is due to the energy consumptions during the use phase. Aluminum as a strong and lightweight material in automobile can significantly reduce the energy consumption of the vehicle compared to a steel solution (both conventional auto steel and advanced high strength steel) and thus help reduce the overall life cycle footprint of the vehicle (Alain Dubreuil et al, 2010; Marlen Bertram et al, 2009; IAI, EAA and AA, 2008; Audi, 2005).

Compared to the production phase, the use phase is usually product specific and is not as straightforward. LCA practitioners shall pay special attention in their approaches to model the use phase so that it can be scientifically sound and practically accurate. This topic, although extremely important, is out of the scope of this study. The study itself is only the foundation for LCA users to build their use phase upon it.

Increased Use and Recycling Can Drive Future Improvements

Looking at the future, the aluminum industry is expected to continuously make progress in reducing product environmental footprints at the production stage. However, the extent of such improvement is often determined by the law of physics.

On the other hand, significant reduction of future life cycle footprints of aluminum products can be achieved through increased aluminum use and through EOL recycling.

As stated previously, the use of aluminum could substantially improve the overall environmental footprint of a product. For instance, aluminum light-weighting solution for passenger cars and light trucks with the assistance of improved powertrains will increase the fuel economy dramatically by 2025 and therefore reduce the overall footprint of the North American passenger fleet. The Ducker Worldwide, an independent material research organization, has forecasted that the use of aluminum in cars and light trucks will be doubled upon the current level by 2025.

Aluminum is a perfect material for recycling and the recycling process does not change any functionality of the metal no matter how many times it is recycled. While aluminum products used for transportation, infrastructure, and building and construction have been historically mostly recycled at the end of life, the recycling rates for consumer products such as certain packaging and consumer electronic products are traditionally very low in North America. It is estimated that a significant amount of aluminum is lost in landfills each year in the region. The recycling of these lost metals will not only help the industry to reduce its environmental footprints, but also help the society to save the metals and its attached energy resources for future generations, thus achieving the ultimate goal of sustainable development for humanity.

7. Peer Review Comments and Answers

7.1 Internal Review Panel Comments and Answers

Q: It would be helpful if the illustrations of roll-up models for the major product systems can be provided.

A: Illustrations were added in Sections 5.2.2, 5.3.2, and 5.3.3. Illustration of the roll-up model of primary aluminum ingot production was shown in **Figure 9**.

Q: Overall, you have created a quality, transparent and credible report. But as you mentioned, it needs work (references, still needs a data quality assessment, etc.) and is way too long.

A: The missing references and data quality assessment have been added.

I agree that the report is too long. The major reason for the level of detail is to ensure transparency. In numerous cases when a life cycle assessment is done, limited information is disclosed without sufficient explanations. In my view, the creditability of the study would be in question in those cases. The ISO standards emphasize transparency as key to LCA studies.

In addition, this study is also intended to be developed into Environmental Product Declarations (EPDs) for aluminum products. EPD has to go through a rigorous third party verification process in which the entire study needs to be scrutinized. A high level of detail in the reporting of the study will certainly help such a process.

Q: Section 3.3.5 refers to a data quality assessment that is not included in the Appendix.

A: The simplified data quality assessment is added to the Appendix.

Q: In Table 14 and Table 15, the PFC (CF_4 and C_2F_6) emissions are equal for both the Prebake and the Söderberg technologies. Is this true?

A: No. The PFC emissions for the two technologies are different in reality. As stated in Section 5.1.1.4.6 and Section 5.1.1.4.7, the emission values are normalized in the input and output tables to comply with relevant laws and regulations on information disclosure since the number of facilities involved in Söderberg technologies is too small.

Q: Page 8, "it is generally considered that the aluminum industry is the industry that involves in partial or all activities inside the enclosed life cycle stages…" – Confusing sentence and needs a reference if it makes a statement such as "it is generally considered."

A: The definition of an industry and its exact boundaries are often conceptual and formed by convention or consensus. In many cases it is also varying significantly by geographic areas and special circumstances. The “official” industry boundary is often drawn by government agencies for statistical or policy purposes and it may not reflect the general concept of the public. For this reason, the report here is simply stating “convention” and a reference is unfortunately not be able to drawn.

Q: Page 18, second paragraph, “it is our understanding that most trade associations…” – What proof or references do we have for this statement?

A: The author is simply talking about a common practice in many industries and would not want to point to any specific names or give any precise sources since it’s unnecessary and irrelevant to this report.

Q: “Reading the executive summary, the discussion regarding industry coverage was limited and did not provide insight to the range of coverage by product systems”.

A: Industry coverage information is added to the Executive Summary.

Q: “I applaud the statements which encourage the ability to replicate the study without specific software requirements. To assist this goal, I recommend providing the conversion of kWh to CO2e for the electrical power mix used in primary aluminum production (Table 13) which I assume is based on GaBi datasets. It is especially important given the large contribution of this step to CO2e emissions”.

A: I understand the convenience for users if we do so. However, the calculations of CO_2 and other greenhouse gas emissions of the electric power mix are based on GaBi 6.0. The data embedded in these calculations is the copyrights of GaBi. For this consideration, we will not be able to provide greenhouse gas intensity information for each kWh of electricity consumption of the power mix.

Q: Glad to see separate datasets for aluminum recycling and secondary aluminum ingot production.

A: This is intended to give users flexibility for their specific applications. Most importantly, aluminum recycling and secondary aluminum production represent fundamentally different concepts from an environmental point of view: aluminum recycling is a process of material recovery from the waste stream while secondary aluminum production is to produce aluminum ingots that meet product specifications defined by downstream users.

Q: Provide energy inputs not only in MJ, but also in kg or m3, and sum up the calorific value of energy inputs (in MJ) to give total energy within each input table (this is done in some table in the EAA report and makes data comparison easier).

A: The original energy reporting from individual facilities varied significantly in terms of reporting units, including BTU, MMBTU, MJ, therm, dekatherm, gallon, cubic feet,

cubic meter, liter, etc. In the data aggregation process, we converted all of them into MJ in terms of net calorific value by using the Energy Information Agency's (EIA) conversion factors. To convert it back and give metric units on the weight or volume of the energy inputs will make the matter more confused and cause unnecessary errors.
In addition, giving the sum of net calorific value without pointing to a specific energy format (fuel types) will be misleading and does not reflect the primary energy consumption situation. The total energy in terms of primary energy demand is listed in the rolled-up LCI tables for each of the major product systems.

Q: Publish the data in the excel format as the IAI did (it makes it much easier for the user to extract and use the data).

A: I fully understand this request. However, the IAI global primary aluminum dataset is generated by using different tools. In addition, the IAI dataset is dealing with a single product system. In our case, the GaBi tool and the multiple product systems make things complicated. The current information provided will allow users to either use the assessment results directly, or to construct their own models by using the input and output tables of the unit production processes and the illustrations of the roll-up models of each product systems.

Q: Talking about CO2 in some part of the report and about CO_2 equivalent in other parts might create confusion among the readers.

A: I understand this concern. LCA is highly technical and the terminologies used are usually not familiar to non-practitioners and general consumers. As it was stated in Section 5.1.3, "…unlike the Life Cycle Inventory, which only reports sums for individual emissions, the LCIA includes methodologies for weighting and combining different emissions into a metric for the **potential impacts** of significant Life Cycle Inventory". The CO_2 emissions are listed in the "inventory" sections of the report and refer to carbon dioxide emissions only, while the CO_2 equivalents are presented in the "impact assessment" sections and refer to the global warming potential of both carbon dioxide and other greenhouse gases converted to the CO_2 equivalent for the existence of 100 years in the atmosphere.

7.2 External Review Comments and Answers

Critical Review by Independent Third Party

In the capacity as the *original study commissioner and practitioner*, The Aluminum Association commissioned an Independent Third Party review of the *Environmental Footprint of Semi-Finished Aluminum Products in North America: A Life-Cycle Assessment Report*, per the operating procedures of UL Environment. The following is a summary of the review results of the *Draft Report*, September 2013.

Reviewer

Thomas P. Gloria, Ph.D., LCACP,
Managing Director, Industrial Ecology Consultants

Critical Review Objectives

Per International Organization of Standardization (ISO) 14044:2006(E) *Environmental management – Life cycle assessment – Requirements and guidelines*, the critical review process included the following objectives to ensure conformance with applicable standards for an ISO conforming Life Cycle Assessment (LCA) study:

- The methods used to carry out the LCA were consistent with the applicable international standards,
- The methods used to carry out the LCA were scientifically and technically valid,
- The data used were appropriate and reasonable in relation to the goal of the study,
- The interpretations reflected the limitations identified and the goal of the study, and
- The study report was transparent and consistent.

In addition, the review process examined necessary revisions to support environmental product declarations (EPDs) of the aluminum semi-manufactured products:

- Flat-rolled Products (excluding foil),
- Extruded Products,
- Shape-Casted Products.

The applicable documents and standards to ensure conformance as a background LCA study include:

- UL Environment *Program Operator Rules*,
- ISO 14025:2006 *Environmental labels and declarations – Type III environmental declarations – Principles and procedures*, and
- Institute Construction and Environment (Bauen und Umwelt) e.V. (IBU) *Product Category Rules for Building-Related Products and Services, Part A: Calculation Rules for the Life Cycle Assessment and Requirements for the Background Report*.

Review Results

On the basis of the goals set forth to review this study, the reviewer concludes that the study generally conforms to the applicable ISO standards as a comprehensive study that may be disclosed to the public. However, at this time the study requires additional non-technical revisions to the report to conform to the applicable documents and standards to support EPDs. The reviewer recognizes that the original intent of the study did not include consideration of supporting EPDs and the authors intend on making the necessary revisions based on the findings of this review.

Respectfully,

Thomas P. Gloria, Ph.D.

19 December 2013
Newton, Massachusetts

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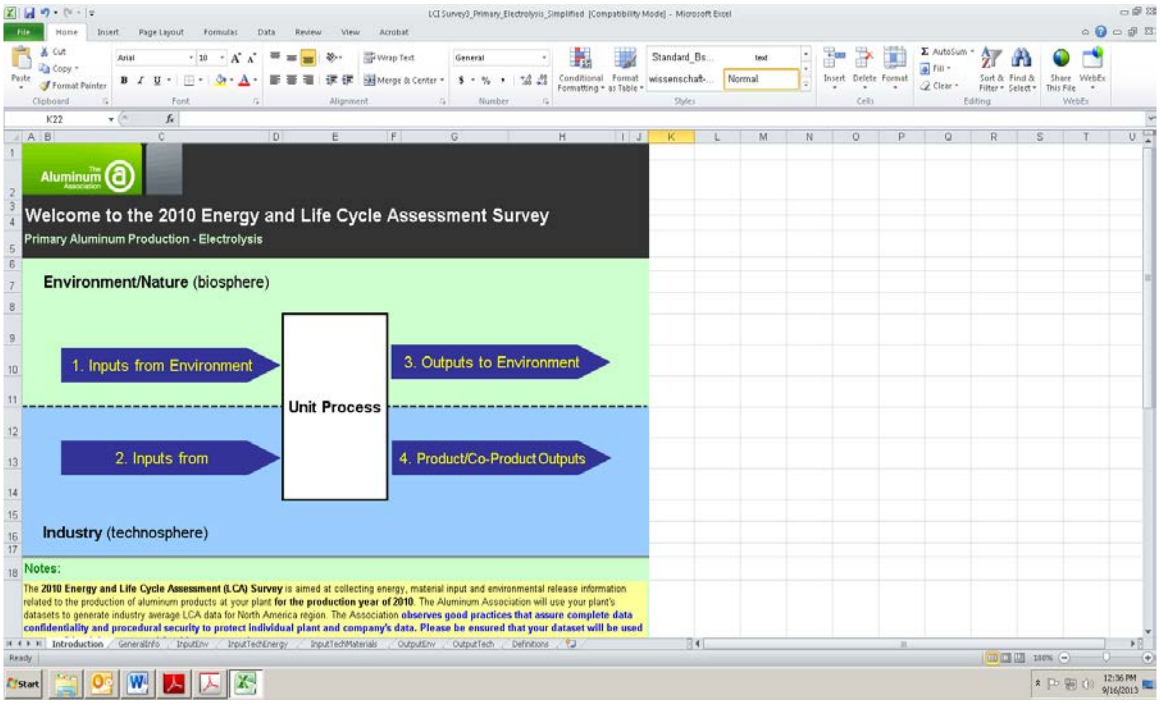
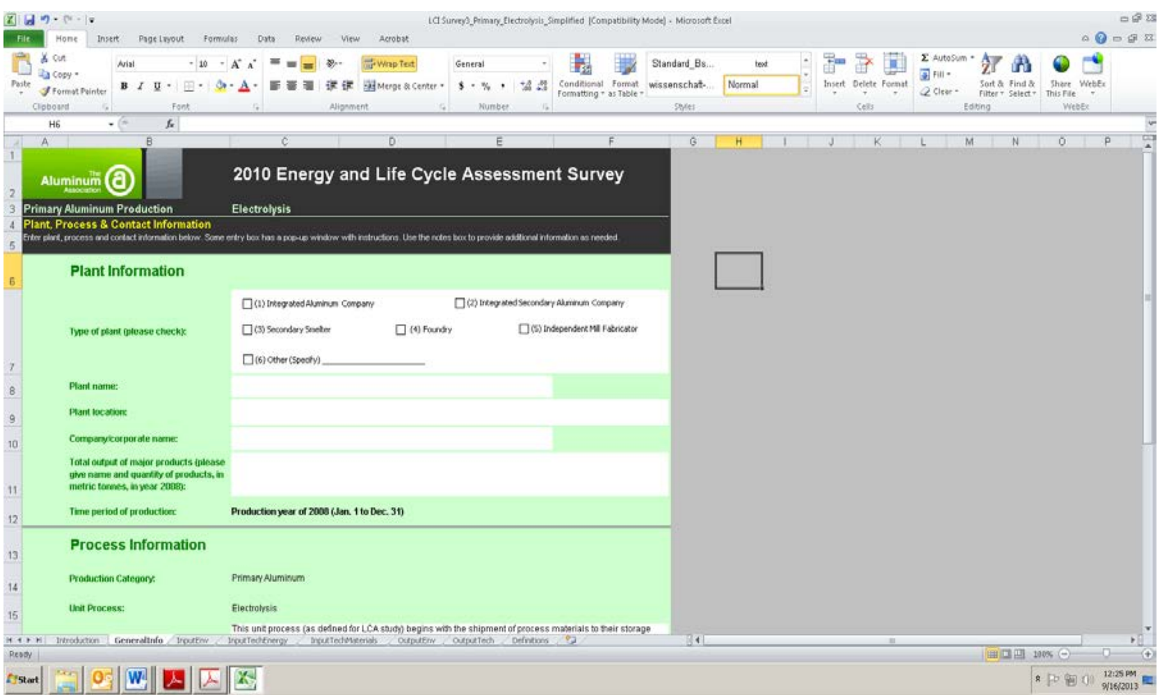
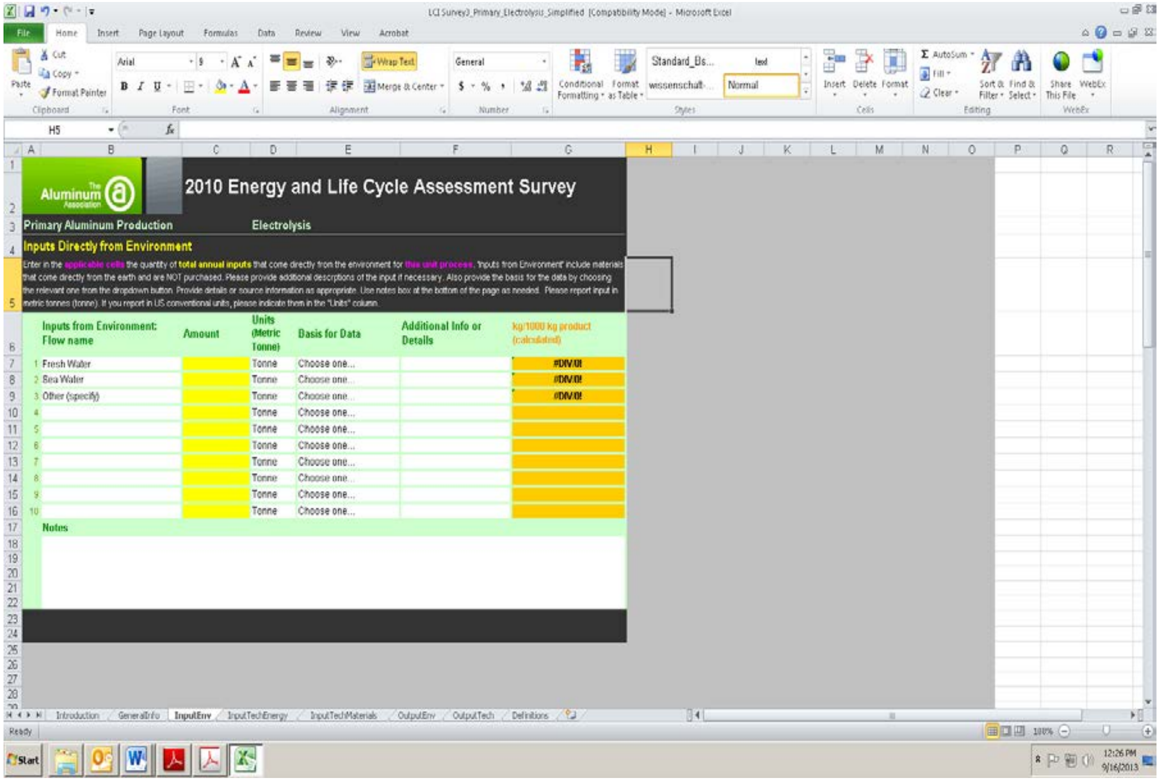
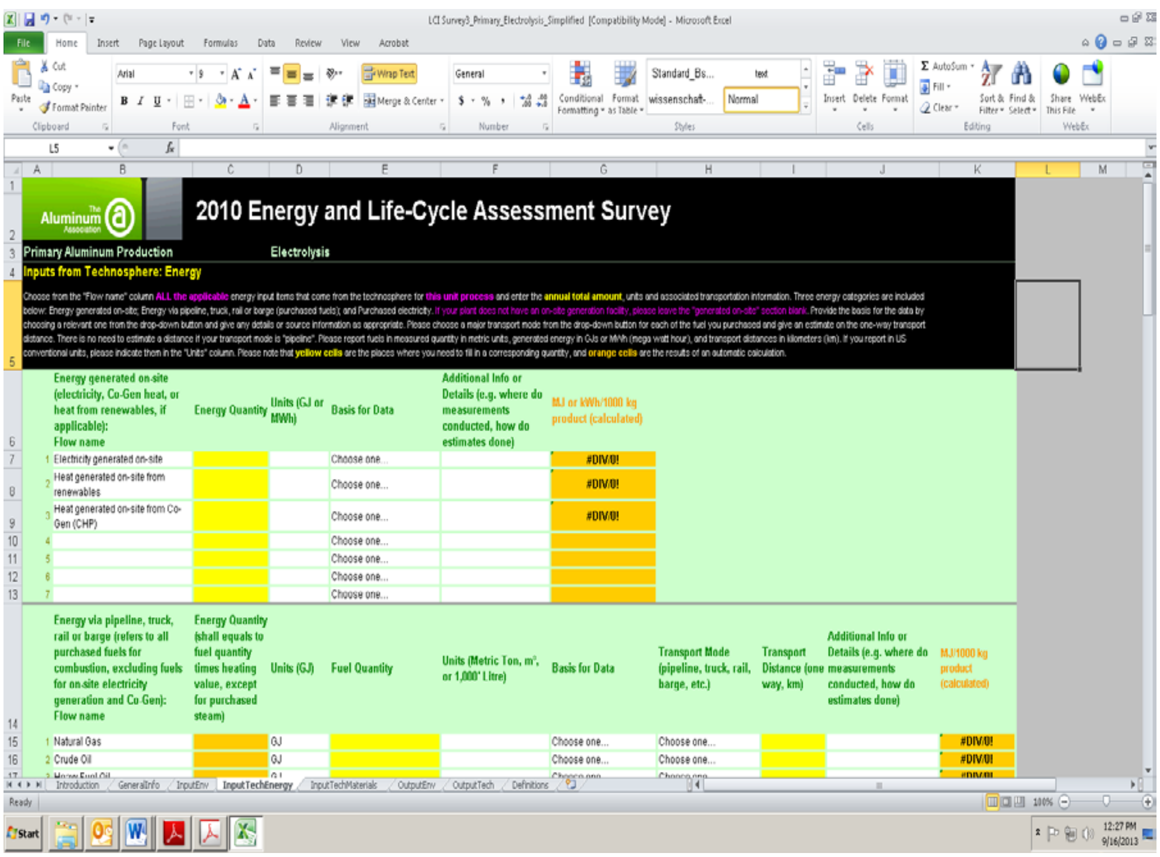
9. Appendix

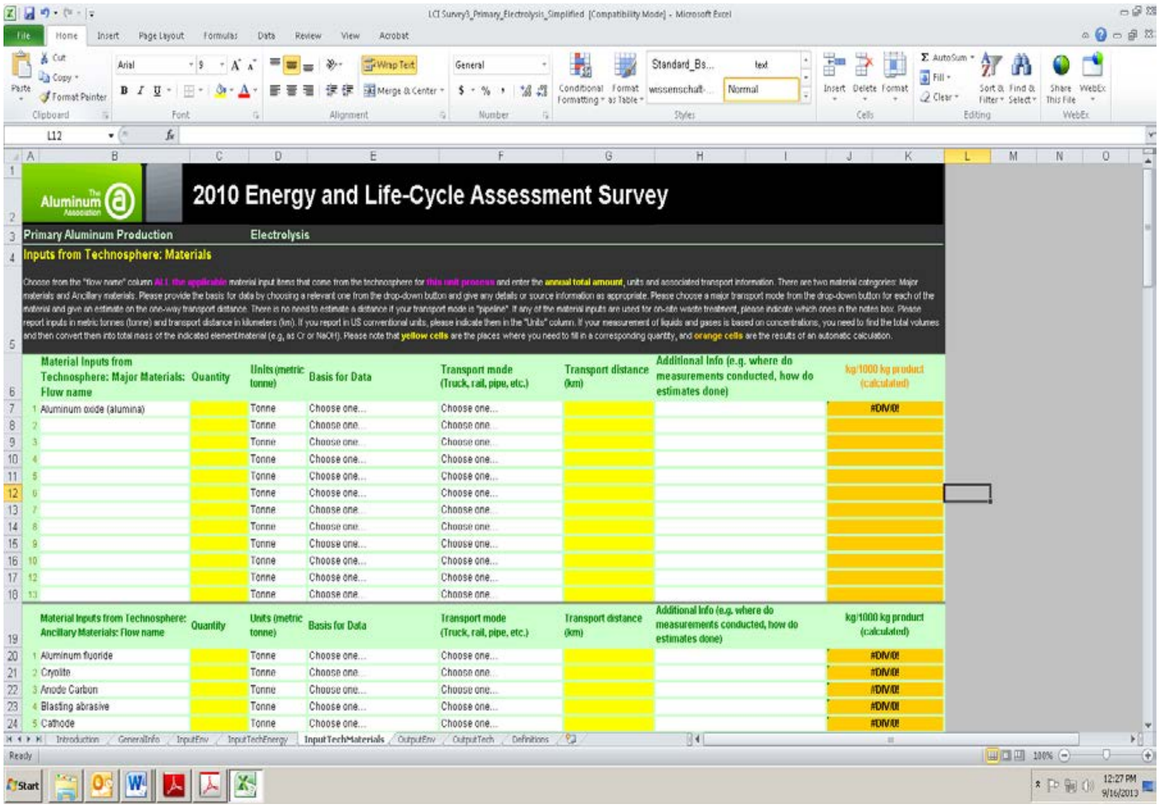
9.1 Samples of Data Survey Forms

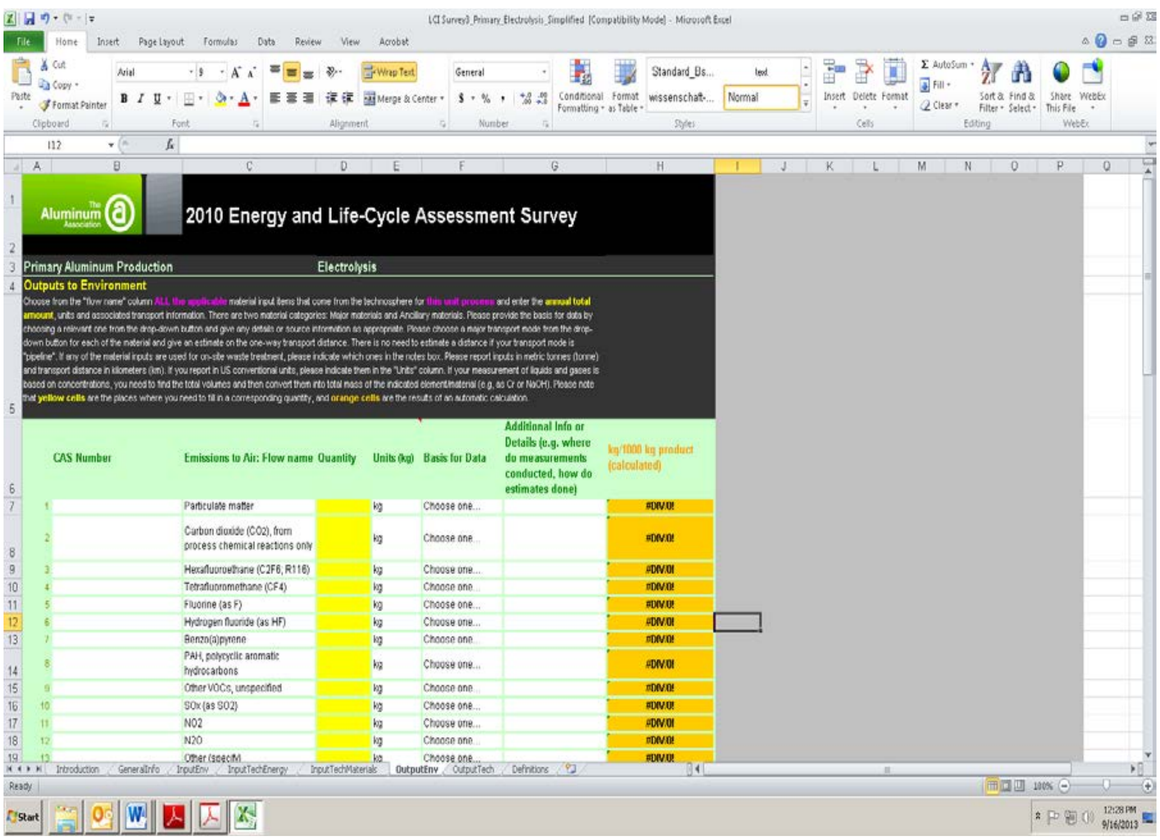


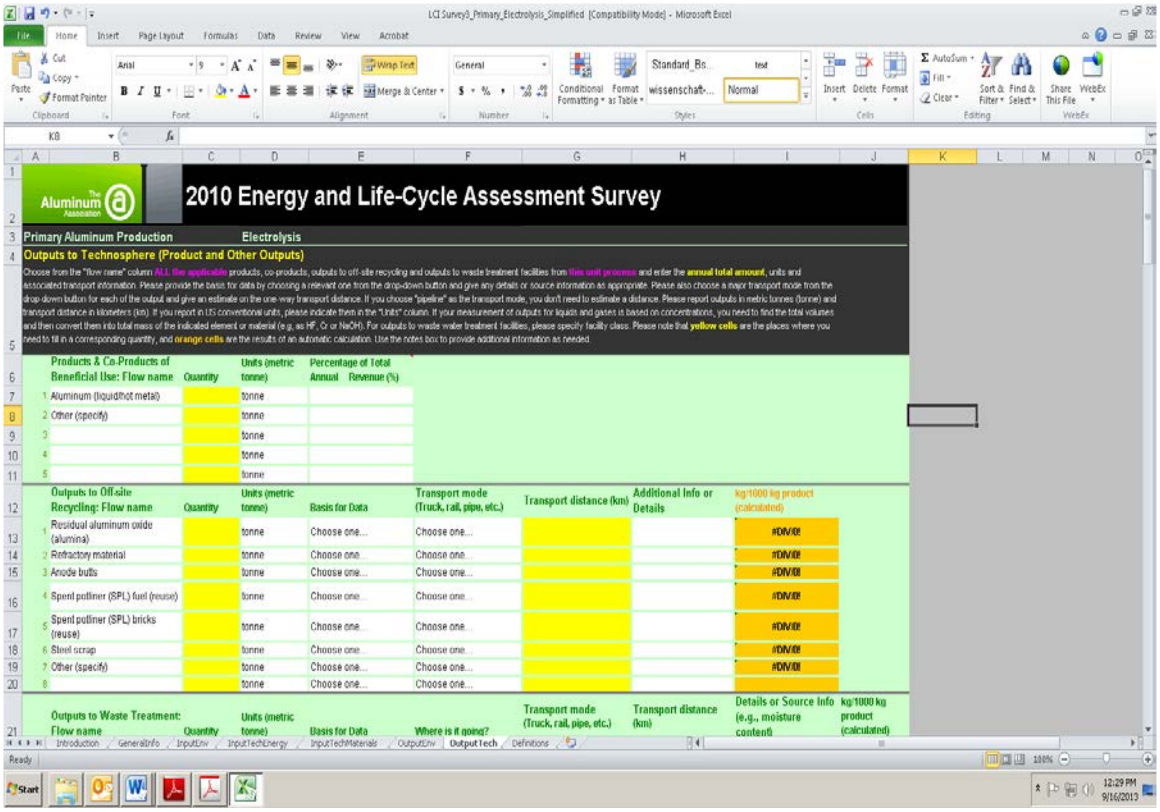



2010 Energy and Life Cycle Assessment Survey
Primary Aluminum Production
Electrolysis
Inputs Directly from Environment
Inputs from Environment: Flow name
Amount
Units (Metric Tonne)
Basis for Data
Additional Info or Details
kg/1000 kg product (calculated)
Fresh Water
Sea Water
Other (specify)
Notes


2010 Energy and Life-Cycle Assessment Survey
Primary Aluminum Production
Electrolysis
Inputs from Technosphere: Energy
Electricity generated on-site
Heat generated on-site from renewables
Heat generated on-site from Co-Gen (CHP)
Natural Gas
Crude Oil


2010 Energy and Life-Cycle Assessment Survey
Primary Aluminum Production
Electrolysis
Inputs from Technosphere: Materials
Material Inputs from Technosphere: Major Materials: Flow name
Quantity
Units (metric tonne)
Basis for Data
Transport mode (Truck, rail, pipe, etc.)
Transport distance (km)
Additional Info (e.g. where do measurements conducted, how do estimates done)
kg/1000 kg product (calculated)
Aluminum oxide (alumina)
Material Inputs from Technosphere: Ancillary Materials: Flow name
Aluminum fluoride
Cryolite
Anode Carbon
Blasting abrasive
Cathode


2010 Energy and Life-Cycle Assessment Survey
Primary Aluminum Production
Electrolysis
Outputs to Environment
CAS Number
Emissions to Air: Flow name
Quantity
Units (kg)
Basis for Data
Additional Info or Details (e.g. where do measurements conducted, how do estimates done)
kg/1000 kg product (calculated)
Particulate matter
Carbon dioxide (CO2), from process chemical reactions only
Hexafluoroethane (C2F6, R116)
Tetrafluoromethane (CF4)
Fluorine (as F)
Hydrogen fluoride (as HF)
Benzo(a)pyrene
PAH, polycyclic aromatic hydrocarbons
Other VOCs, unspecified
SOx (as SO2)
NO2
N2O



2010 Energy and Life-Cycle Assessment Survey

Primary Aluminum Production — **Electrolysis**

Outputs to Technosphere (Product and Other Outputs)

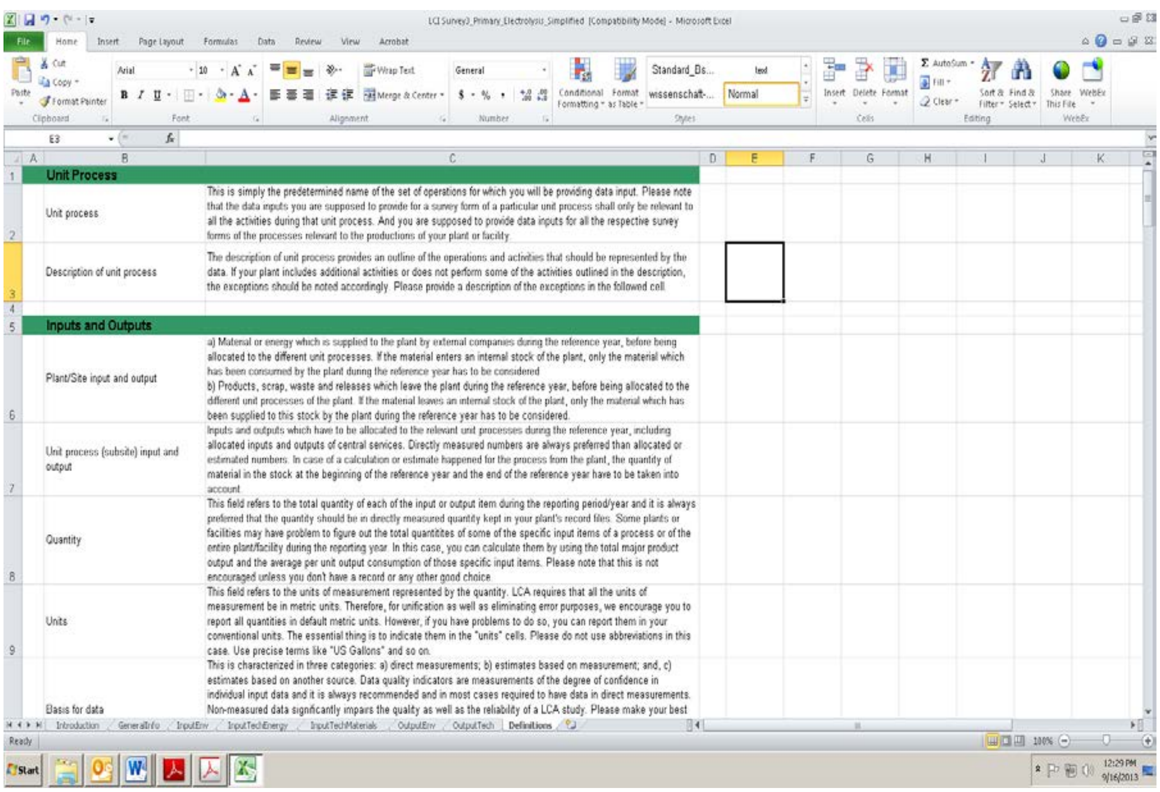
Choose from the "flow name" column ALL the applicable products, co-products, outputs to off-site recycling and outputs to waste treatment facilities from this unit process and enter the annual total amount, units and associated transport information. Please provide the basis for data by choosing a relevant one from the drop-down button and give any details or source information as appropriate. Please also choose a major transport mode from the drop-down button for each of the output and give an estimate on the one-way transport distance. If you choose "pipeline" as the transport mode, you don't need to estimate a distance. Please report outputs in metric tonnes (tonne) and transport distance in kilometers (km). If you report in US conventional units, please indicate them in the "Units" column. If your measurement of outputs for liquids and gases is based on concentrations, you need to find the total volumes and then convert them into total mass of the indicated element or material (e.g, as HF, Cr or NaOH). For outputs to waste water treatment facilities, please specify facility class. Please note that yellow cells are the places where you need to fill in a corresponding quantity, and orange cells are the results of an automatic calculation. Use the notes box to provide additional information as needed.

	Products & Co-Products of Beneficial Use: Flow name	Quantity	Units (metric tonne)	Percentage of Total Annual Revenue (%)
1	Aluminum (liquid/hot metal)		tonne	
2	Other (specify)		tonne	
3			tonne	
4			tonne	
5			tonne	

	Outputs to Off-site Recycling: Flow name	Quantity	Units (metric tonne)	Basis for Data	Transport mode (Truck, rail, pipe, etc.)	Transport distance (km)	Additional Info or Details	kg/1000 kg product (calculated)
1	Residual aluminum oxide (alumina)		tonne	Choose one...	Choose one...			#DIV/0!
2	Refractory material		tonne	Choose one...	Choose one...			#DIV/0!
3	Anode butts		tonne	Choose one...	Choose one...			#DIV/0!
4	Spent potliner (SPL) fuel (reuse)		tonne	Choose one...	Choose one...			#DIV/0!
5	Spent potliner (SPL) bricks (reuse)		tonne	Choose one...	Choose one...			#DIV/0!
6	Steel scrap		tonne	Choose one...	Choose one...			#DIV/0!
7	Other (specify)		tonne	Choose one...	Choose one...			#DIV/0!
8			tonne	Choose one...	Choose one...			

Outputs to Waste Treatment: Flow name	Quantity	Units (metric tonne)	Basis for Data	Where is it going?	Transport mode (Truck, rail, pipe, etc.)	Transport distance (km)	Details or Source Info (e.g., moisture content)	kg/1000 kg product (calculated)

Introduction / GeneralInfo / InputEnv / InputTechEnergy / InputTechMaterials / OutputEnv / OutputTech / Definitions



Unit Process		
Unit process	This is simply the predetermined name of the set of operations for which you will be providing data input. Please note that the data inputs you are supposed to provide for a survey form of a particular unit process shall only be relevant to all the activities during that unit process. And you are supposed to provide data inputs for all the respective survey forms of the processes relevant to the productions of your plant or facility.
Description of unit process	The description of unit process provides an outline of the operations and activities that should be represented by the data. If your plant includes additional activities or does not perform some of the activities outlined in the description, the exceptions should be noted accordingly. Please provide a description of the exceptions in the followed cell.
Inputs and Outputs	
Plant/Site input and output	a) Material or energy which is supplied to the plant by external companies during the reference year, before being allocated to the different unit processes. If the material enters an internal stock of the plant, only the material which has been consumed by the plant during the reference year has to be considered b) Products, scrap, waste and releases which leave the plant during the reference year, before being allocated to the different unit processes of the plant. If the material leaves an internal stock of the plant, only the material which has been supplied to this stock by the plant during the reference year has to be considered.
Unit process (subsite) input and output	Inputs and outputs which have to be allocated to the relevant unit processes during the reference year, including allocated inputs and outputs of central services. Directly measured numbers are always preferred than allocated or estimated numbers. In case of a calculation or estimate happened for the process from the plant, the quantity of material in the stock at the beginning of the reference year and the end of the reference year have to be taken into account.
Quantity	This field refers to the total quantity of each of the input or output item during the reporting period/year and it is always preferred that the quantity should be in directly measured quantity kept in your plant's record files. Some plants or facilities may have problem to figure out the total quantitites of some of the specific input items of a process or of the entire plant/facility during the reporting year. In this case, you can calculate them by using the total major product output and the average per unit output consumption of those specific input items. Please note that this is not encouraged unless you don't have a record or any other good choice.
Units	This field refers to the units of measurement represented by the quantity. LCA requires that all the units of measurement be in metric units. Therefore, for unification as well as eliminating error purposes, we encourage you to report all quantities in default metric units. However, if you have problems to do so, you can report them in your conventional units. The essential thing is to indicate them in the "units" cells. Please do not use abbreviations in this case. Use precise terms like "US Gallons" and so on.
Basis for data	This is characterized in three categories: a) direct measurements; b) estimates based on measurement; and, c) estimates based on another source. Data quality indicators are measurements of the degree of confidence in individual input data and it is always recommended and in most cases required to have data in direct measurements. Non-measured data significantly impairs the quality as well as the reliability of a LCA study. Please make your best

Introduction / GeneralInfo / InputEnv / InputTechEnergy / InputTechMaterials / OutputEnv / OutputTech / Definitions

9.2 List of Companies Provided Data

1. Alcoa Inc.
2. Aleris International Inc.
3. Alexandria Extrusion Company
4. Century Aluminum Company
5. Constellium
6. Grupo Cuprum
7. Hydro Aluminum North America
8. Jupiter Aluminum Corporation
9. Kaiser Aluminum
10. KB Alloy
11. Logan Aluminum
12. Metal Exchange Corporation
13. Minalex Corporation
14. Nichols Aluminum
15. Noranda Aluminum Inc.
16. Novelis Inc.
17. Ormet Corporation
18. Peerless of America
19. Penn Aluminum International LLC
20. Rio Tinto Alcan
21. Sapa Extrusions Inc.
22. Scepter Inc.
23. Sherwin Alumina
24. Smelter Service Corporation
25. Tri-Arrows Aluminum Inc.

9.3 Data Quality Assessment

Data quality was evaluated using the Weidema methodology as described in the International Journal of LCA 3 (5) page 259-265; 1998, Weidema et al.; LCA data quality. The following tables show the evaluation matrix and the evaluation.

Score:	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert);	Non-qualified estimate
Representativeness/ Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data from from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/ or from shorter periods
Temporal correlation	Less than 3 years of difference to reference year	Less than 6 years of difference to reference year	Less than 10 years of difference to reference year	Less than 15 years of difference to reference year	Age of data unknown or more than 15 years of difference to reference year
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area (with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but similar technology.	Data on related processes or materials but different technology.

Data Category	Reliability of Source	Representativeness /Completeness	Temporal Correlation	Geographical Correlation	Further Technological Correlation
Bauxite Mining	1	1	1	2	1
Alumina Refining	1	1	1	2	1
Anode Production	1	1	1	2	1
Electrolysis	1	1	1	1	1
Ingot Casting	1	1	1	1	1
Scrap Processing	1	1	1	1	1
Scrap Melting and Casting	1	1	1	1	1
Extrusion	1	1	1	1	1
Hot Rolling	1	1	1	1	1
Cold Rolling	1	1	1	1	1
Shape Casting	2	4	3	3	2

9.4 Bio of External Peer Reviewer (s)

THOMAS GLORIA
Managing Director
Industrial Ecology Consultants
www.industrial-ecology.com

Thomas P. Gloria, Ph.D. is Managing Director of Industrial Ecology Consultants. He has more than 20 years of professional experience in sustainability management consulting and information technology engineering design. His work encompasses corporate sustainability strategy; product innovation; environmental life cycle assessment (LCA) and management (LCM); enterprise and product level greenhouse gas emissions tracking; and energy efficiency feasibility analysis.

Dr. Gloria is a member of the Board of Directors of the American Center for Life Cycle Assessment. Dr. Gloria also serves on the General Motors Company Sustainability Stakeholder Committee under the auspices of Ceres. He regularly lectures for the Harvard University Extension School, Tufts University, the Bainbridge Graduate Institute, and the Presidio Graduate School.

Tom has worked with several private & public sector clients conducting sustainability related work including: Armstrong World Industries, Avery Dennison, Biogen IDEC, Cargill, Chevron, Church & Dwight (Arm & Hammer brand), Covidien, EILEEN FISHER, ExxonMobil, Herman Miller, Industrial Economics Inc., Interface, International Zinc Association, International Copper Association, International Council on Mining & Metals, Iron Ore Company of Canada, Kimball Furniture, Kraft Foods, Levi Strauss & Co., Nestle Waters North America, News Corporation, Nike, Oregon Department of Environmental Quality, Rio Tinto, Sears Holdings Corporation, SC Johnson, Samsung, Silgan Containers, Steelcase, Timberland, U.S. EPA, U.S. Department of Commerce. He holds a Ph.D. and M.S. in Civil and Environmental Engineering from Tufts University and a B.Sc. in Electrical and Computer Science Engineering from the University of Connecticut.