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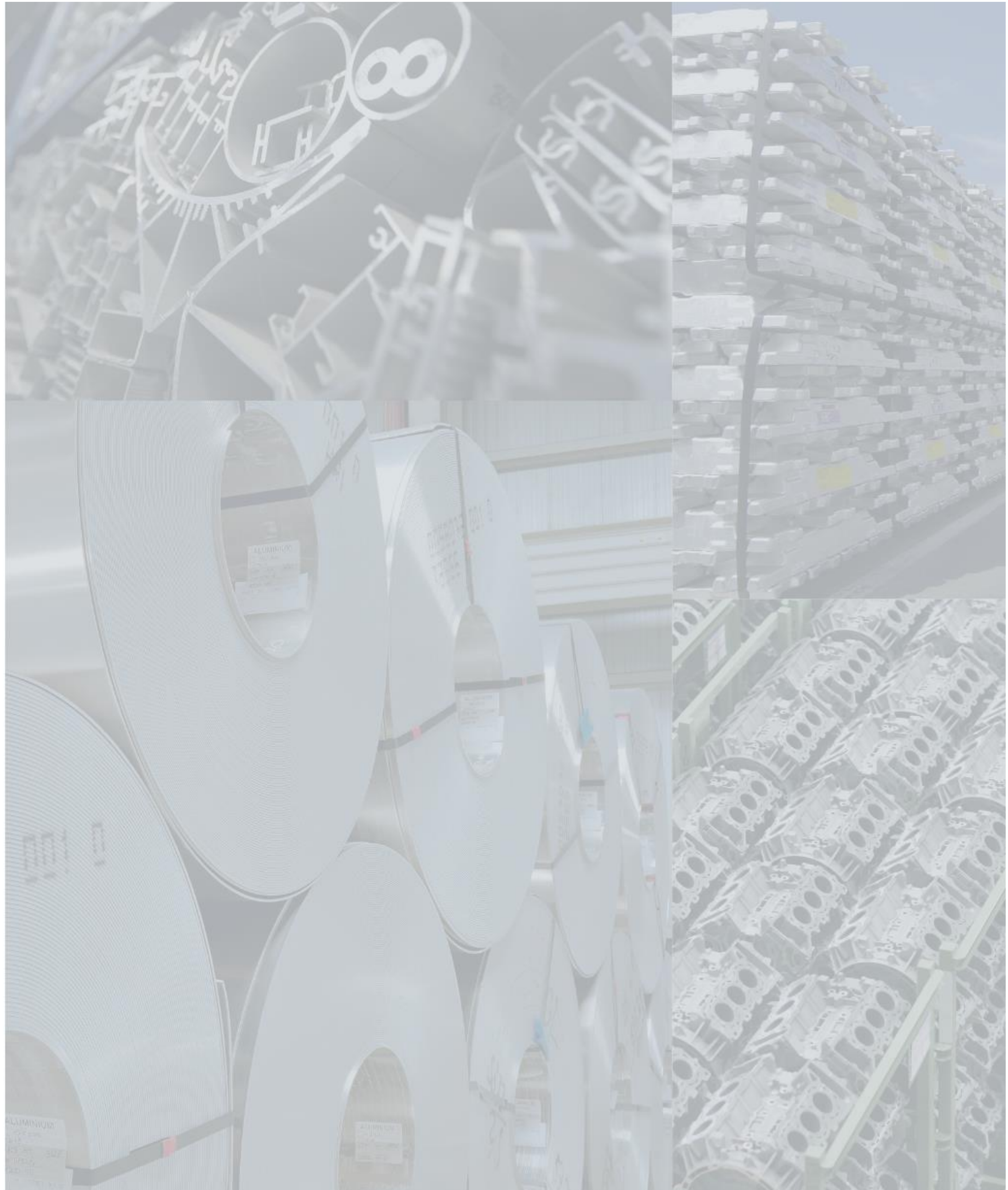
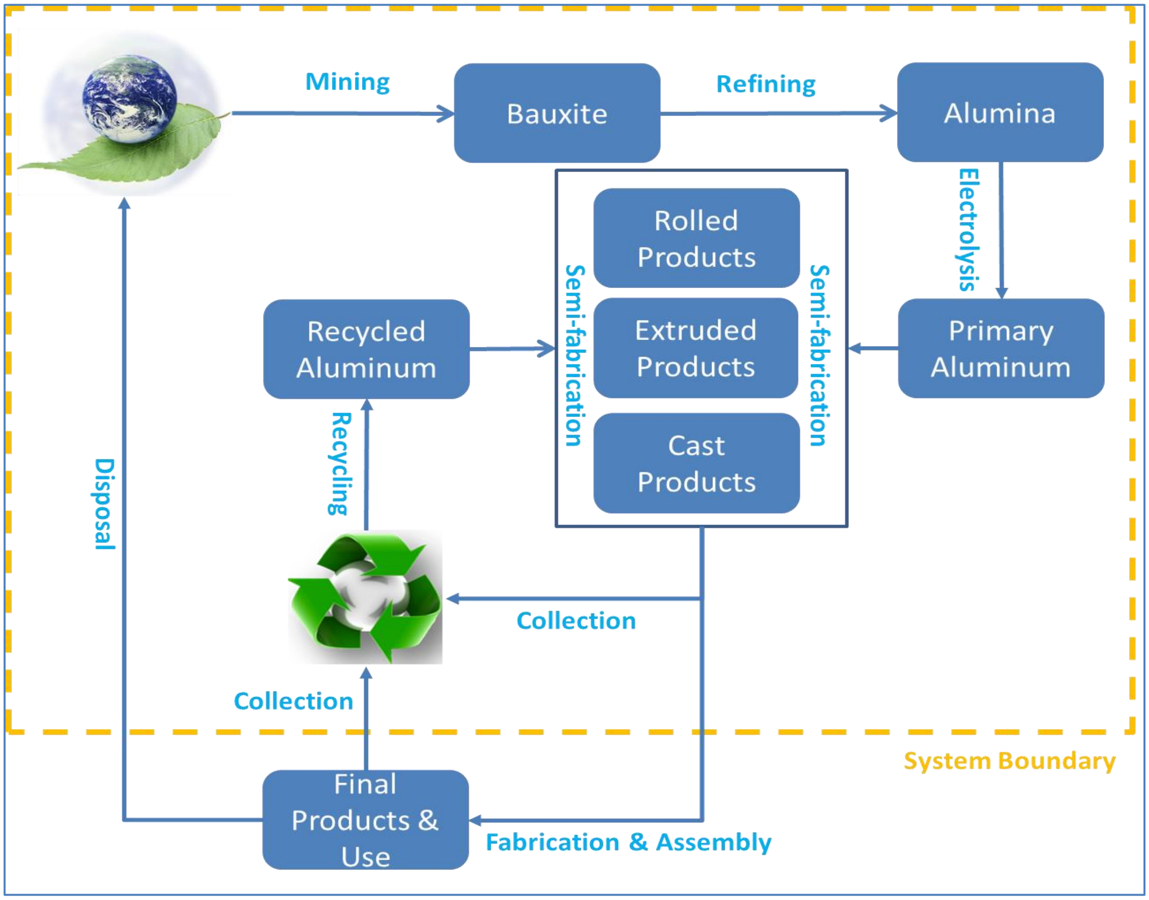


JANUARY 2022

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

A LIFE CYCLE ASSESSMENT REPORT

PREPARED BY (MARSHALL) JINLONG WANG



Acknowledgment

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Glossary

Life Cycle

A view of a product system as “consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal” (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land and water.

Life Cycle Assessment (LCA)

“Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 14040:2006, section 3.2)

Life Cycle Inventory (LCI)

“Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle” (ISO 14040:2006, section 3.3)

Life Cycle Impact Assessment (LCIA)

“Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product” (ISO 14040:2006, section 3.4)

Life Cycle Interpretation

“Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations” (ISO 14040:2006, section 3.5)

Functional Unit

“Quantified performance of a product system for use as a reference unit” (ISO 14040:2006, section 3.20)

Allocation

“Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO 14040:2006, section 3.17)

Closed-loop and Open-loop Allocation of Recycled Material

“An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.”

“A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.” (ISO 14044:2006, section 4.3.4.3.3)

Foreground System

“Those processes of the system that are specific to it … and/or directly affected by decisions analyzed in the study.” (JRC 2010, p. 97) This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Background System

"Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good…." (JRC 2010, pp. 97-98) As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Critical Review

"Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment" (ISO 14044:2006, section 3.45).

Primary Aluminum

Unalloyed aluminum produced from alumina, typically by electrolysis, and with an aluminum content of 99.7%.

Ingot

Cast product intended and suitable for remelting or forming by hot or cold working.

Primary Aluminum Ingot

Ingot of unalloyed or alloyed aluminum cast from primary aluminum and possibly a small amount of runaround scrap (within the smelter's cast house).

Recycled Aluminum Ingot

Aluminum ingot obtained by recycling of scrap.

- NOTE: The term "secondary aluminum" should be avoided for this concept.

Rolling Ingot

Ingot intended or suitable for rolling.

Extrusion Ingot

Ingot intended and suitable for extruding, typically of solid circular cross-section, sometimes with a central hollow or a flattened cross-section.

Extrusion Billet

Extrusion ingot cut to length.

Extrusion Log

Extrusion ingot not cut to length.

Alloy

Substance having metallic properties and composed of two or more elements, so combined that they cannot readily be separated by physical means.

Casting Alloy

Alloy primarily intended for the production of castings.

Wrought Alloy

Alloy primarily intended for the production of wrought products by hot and/or cold working.

Heat-treatable Alloy

Alloy which can be strengthened by suitable thermal treatment.

Non-heat-treatable Alloy

Alloy which is primarily strengthened only by working and not by thermal treatment.

Semi-Fabrication

Aluminum semi-fabrication is a forming process to transform aluminum ingots into a semi-finished shape. Typical aluminum semi-fabrication processes include rolling, extrusion, forging and casting. Product of a semi-fabrication process often requires further manufacturing (fabrication, finishing, and assembly) to turn it into a final product for end use.

Unwrought Product

Product obtained by casting without further hot or cold working, e.g., ingots for rolling, ingots for extruding, ingots for forging, ingots for remelting, cast plate or castings.

Wrought Product

Product that has been subjected to hot working and/or cold working.

Semi-fabricated (Semi-finished) Product

Product that has undergone some processing and is supplied for further processing before it is ready for use. Semi-finished product may be treated (surface treatment, thermal treatment, etc.) and/or coated.

- NOTE: Semi-finished products include wrought products and castings. It does not include ingots and billets.

Rolling

The forming of solid metal in a gap between two rotating cylinders. The resulted product is sheet, plate or foil.

Hot Rolling

Rolling after preheating.

- NOTE 1: The purpose of hot rolling is typically to improve the efficiency of the rolling process.
- NOTE 2: Surface finish and dimensional tolerance control of hot rolled metal are generally inferior to cold rolled metal.

Cold Rolling

Rolling without preheating.

Sheet

Rolled product that is rectangular in cross section with nominal thickness less than 6 mm (in USA less than 0.250 inches [6.3 mm]) but not less than 0,20 mm (in USA greater than 0.006 inches [0.15 mm]) and with slit, sheared or sawed edges.

Plate

Rolled product that is rectangular in cross section and with thickness not less than 6 mm (in USA not less than 0.250 inch) with sheared or sawn edges.

Hot Rolled Sheet/Hot Rolled Plate

Sheet or plate the final thickness of which is obtained by hot rolling.

Cold Rolled Sheet/Cold Rolled Plate

Sheet or plate the final thickness of which is obtained by cold rolling.

Mill Finish Sheet/Plate

Sheet/plate having a finish defined by the actual roll grinding and rolling conditions, without further specification from a customer or a standard.

- NOTE: The finish of mill finish sheet/plate can vary from sheet to sheet or within one sheet.

Clad Sheet/Clad Plate

Sheet or plate consisting of an aluminum core to which a thin layer of aluminum or another metal is metallurgically bonded on one side or on both sides, typically by rolling.

Extrusion

Process in which a billet in a container is forced under pressure through an aperture of a die.

Extruded Profile

Profile brought to final dimensions by extruding.

Forging

Wrought product formed by hammering or pressing, typically when hot, between open dies (hand forging) or closed dies (drop or die forging).

Casting

Process in which molten metal is introduced into a mold where it solidifies.

Sand Casting

Casting process in which molten metal is poured into a sand mold and solidified.

Permanent Mold Casting

Casting process in which molten metal is introduced by gravity or low pressure into a mold constructed of durable material, typically iron or steel.

- NOTE: A permanent mold casting process where the metal solidifies in a metal mold under low pressure (typically less than 1 bar above atmospheric pressure) is also referred to as "low pressure die casting process".

Die Casting

Casting process in which molten metal is introduced under substantial pressure, typically above 100 bars into a metal die.

- NOTE: Also referred to as "pressure die casting (process)" or "high pressure die casting (process)".

Direct Chill (DC) Casting

Casting process in which molten metal is solidified in a water-cooled open-ended mold from the outlet of which water is directly applied to the emerging ingot.

Continuous Casting

Casting process in which molten metal is solidified rapidly in a cooled mold and continuously withdrawn and cut while the mold is being simultaneously replenished with liquid metal.

Coating

Process in which a coating material is applied on a metallic substrate, including cleaning and chemical pretreatment.

- NOTE 1: This term covers a one-side or two-side, single or multiple application of liquid or powder coating materials which are subsequently cured.
- NOTE 2: This term also covers laminating with plastic films.

Aluminum Scrap

Raw material, destined for trade and industry, mainly consisting of aluminum resulting from the collection and/or recovery of metal that arises as waste at various production stages; or products after use to be used for the production of wrought and cast alloys and for other production processes.

New Scrap

Also called pre-consumer scrap, is the scrap arising from the various production stages of aluminum products, before the aluminum product is sold to the final user (e.g., scrap generated by industrial or manufacturing process). Excluded from this definition is internal or run-around scrap. Pre-consumer scrap is usually generated from different sites where scrap is re-melted.

Internal Scrap

New scrap generated in-house by industrial or manufacturing process. Internal scrap can be immediately introduced back to a remelting furnace on-site and reutilized without substantial treatment. Substantial treatment refers to significant thermal or chemical processes such as melting, purifying and/or alloying. In general, the quantity of internal scrap in each production cycle is about the same. The quantity of internal scrap normally does not affect the material balance sheet (raw material in and product out) of a facility.

- NOTE 1: Internal scrap is not traded on the market and typically does not appear in trade statistics.
- NOTE 2: Also known as turn-around scrap, in-house scrap, run-around scrap or home scrap.

Old Scrap

Also called post-consumer, is scrap arising from products after use. It is generated by the retirement of consumer or industrial products such as auto parts, beverage containers, durable goods, wire and cable, window frames, machinery parts, etc.

Traded Scrap

Scrap that is traded on the market.

- NOTE: Traded scrap typically meets requirements on characteristics agreed upon between supplier and purchaser.

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0. Executive Summary

This report documents the life cycle inventory and impact assessment (LCI and LCIA) results of **1,000 kilograms (1 metric ton) primary, recycled and semi-fabricated aluminum products manufactured in North America (U.S. and Canada) in the production year of 2016**. The study is an update to a previous study published in 2013 to respond to increasing market demand for up-to-date life cycle assessment (LCA) data to help the aluminum industry and its stakeholders, LCA practitioners, academic researchers and other interested parties better understand the potential environmental impact of aluminum products.

A life cycle assessment of a product quantifies all material and energy use, all environmental releases, and the potential environmental impacts over its entire life cycle from raw material acquisition through to ultimate recycling and/or disposal. The functional unit of the study is 1,000 kg aluminum in various forms. The study includes both "***cradle-to-gate***" and "***cradle-to-grave***" LCAs. Cradle-to-gate refers to life cycle stages from the extraction of raw materials to the completion of "products" (i.e., ingot, sheet, extrusion, casting, etc.). Cradle-to-grave refers to life cycle stages from the extraction of raw materials to the recycling or disposal of end-of-life (EOL) products. **Excluded in the study are final product forming and assembly, as well as the product's use phase**.

To be specific, the "products" (or product systems) of this study include:

- primary aluminum ingot;
- recycled aluminum ingot;
- extruded aluminum including both generic products and products for automotive applications;
- aluminum sheet including non-automotive and non-can sheet, and sheet for automotive applications;
- aluminum foil; and
- die cast products.

Original production data (primary data) of each individual unit process was directly collected either by the Aluminum Association (AA) or the International Aluminium Institute (IAI), from more than 100 production facilities representing a large majority of the industry in Canada and the United States. The methodology used for the goal and scope definition and inventory analysis is consistent with the methodology described in the ISO 14040/14044 Standards. ***Cradle-to-gate LCA*** models are developed by using a ***cut-off method***. Meanwhile, ***cradle-to-grave LCA*** models are developed by using ***a net scrap substitution approach,*** which is ***a variant of the substitution method***.

A **transparent approach** is taken for this study throughout the processes including data collection, modeling, and reporting. Information is disclosed at a maximum level where it is legally permitted. All significant inventories are listed. And a combination of results is provided for users with different purposes.

The intended use of the study is to:

- Establish an up-to-date life cycle inventory 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 assessment of alternative design options (for instance, alternative process design, technology, etc.), compare corresponding datasets (benchmarking), and guide the evaluation of modifications for improvement;
- Provide information for use in strategic planning and sustainable development;
- Develop communication messages such as Carbon Footprint of Products (CFPs), Environmental Product Declarations (EPDs), and industry sustainability reports.

The study is not intended for:

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

0.1 Results

The results of the study, in terms of "***cradle-to-gate***" and "***cradle-to-grave***" potential environmental impacts, are shown in **Table 0-1**, **Table 0-2**, **Table 0-3**, **Table 0-4** and **Table 0-5**. Note that the ***cradle-to-gate*** results for semi-fabricated products are based on **the weighted average of the actual mix of primary and recycled aluminum feedstock** reported by all survey responders for the baseline production year of 2016. The ***cradle-to-grave*** results, on the other hand, are based on **an assumed EOL recycling rate of 95 percent** for each product system. It is a snapshot of ***potential life cycle impacts*** of the products when the use phase is excluded and when the indicated EOL recycling rate is achieved. Different assumptions for EOL recycling rates will generate very different cradle-to-grave results. From this perspective, the report also provides additional information to assist users to calculate results under different recycling rates.

Table 0-1: Cradle-to-gate LCIA results for the production of 1,000 kg of domestic primary aluminum in North America

Assessment parameter	Unit	Bauxite mining	Alumina refining	Electrolysis	Cast house	Total
Primary energy demand	GJ	0.61	32.87	99.93	1.91	135.32
Global warming potential	kg CO2e	48.49	2801.58	5489.62	115.62	8455.31
Acidification potential	kg SO2e	0.24	10.96	25.54	0.25	36.99
Eutrophication	kg Ne	0.01	0.47	0.33	0.01	0.82

potential						
Smog formation potential	kg O3e	2.81	184.31	81.35	5.40	273.87

Table 0-2: Cradle-to-gate LCIA results for the consumption mix of 1,000 kg of primary aluminum in North America

Inventory parameter	Primary energy demand (GJ)	Global warming potential (kg CO2 eq.)	Acidification potential (kg SO2 eq.)	Eutrophication potential (kg N eq.)	Smog formation potential (kg O3 eq.)
North America	109.88	6865.71	30.03	0.67	222.38
Russia	12.81	639.65	3.43	0.08	38.65
U.A.E.	5.62	423.68	2.11	0.06	33.52
Argentina	2.71	193.28	0.99	0.02	8.27
Venezuela	1.04	73.93	0.38	0.01	3.16
Bahrain	0.48	36.04	0.18	0.01	2.85
Brazil	0.41	29.09	0.15	0.00	1.25
Rest of World	2.75	253.14	1.35	0.04	16.08
Total	**135.69**	**8514.52**	**38.62**	**0.88**	**326.17**

Table 0-3: Cradle-to-gate LCIA results for aluminum recycling, representing 1,000 kg of recovered aluminum from scrap in North America

Assessment Parameter	Unit	Scrap Processing, Melting and Casting	Dross & Salt Cake Recycling	Primary Ingot	Total
Primary energy demand	GJ	9.14	0.04	0.00	9.18
Global warming potential	kg CO2e	524.59	2.13	0.00	526.71
Acidification potential	kg SO2e	0.86	0.00	0.00	0.87
Eutrophication potential	kg Ne	0.04	0.00	0.00	0.04
Smog formation potential	kg O3e	15.56	0.08	0.00	15.64

Table 0-4: Cradle-to-gate LCIA results of semi-fabricated aluminum products, representing 1,000 kg of products

Assessment	Extrusion	Sheet	Foil	Die Cast	Automotive	Automotive

Parameter					Extrusion	Sheet
Primary energy demand (GJ)	102.38	66.72	78.87	48.76	78.97	126.14
Global warming potential (kg CO2 e.)	6213.22	3978.32	4653.41	2898.98	4739.43	7744.79
Acidification potential (kg SO2 e.)	23.77	13.81	15.39	9.66	17.04	31.68
Eutrophication potential (kg N e.)	0.64	0.39	0.46	0.28	0.49	0.79
Smog formation potential (kg O3 e.)	225.73	140.21	159.59	96.23	169.01	287.04

Table 0-5: Cradle-to-grave LCIA results of semi-fabricated aluminum products, representing 1,000 kg of products, assuming a 95 percent EOL recycling rate

Assessment Parameter	Extrusion	Sheet	Foil	Die Cast	Automotive Extrusion	Automotive Sheet
Primary energy demand (GJ)	46.28	49.79	57.30	29.25	45.93	35.96
Global warming potential (kg CO2 e.)	2667.42	2903.98	3286.18	1666.76	2649.77	2044.85
Acidification potential (kg SO2 e.)	6.99	8.74	8.94	3.82	7.16	4.69
Eutrophication potential (kg N e.)	0.27	0.28	0.32	0.16	0.27	0.19
Smog formation potential (kg O3 e.)	88.04	98.75	106.75	48.38	87.98	65.54

This study concludes with the following take-away messages:

0.2 Cradle-to-Gate

0.2.1 Energy Demand: Key Driver of Environmental Footprint

From a ***cradle-to-gate*** perspective, **most of the environmental footprint of the examined product systems is energy related**. The generation of electricity, particularly from fossil fuel fired power plants, contributes the largest share of the total footprint.

The attribution of electricity to the overall footprint is directly related to the use of primary aluminum as a feedstock. **Although primary aluminum is only a small share of the raw material input in many of the examined semi-fabricated product systems, it nevertheless accounts for *more than 40 percent* of the environmental impact for most products** (**Figure 0-1** and **Figure 0-2**). The remelting & casting process, which melts scrap and raw metal to produce fabrication ingots, is the next resource and emission intensive process, followed by semi-fabrication such as rolling and extrusion.

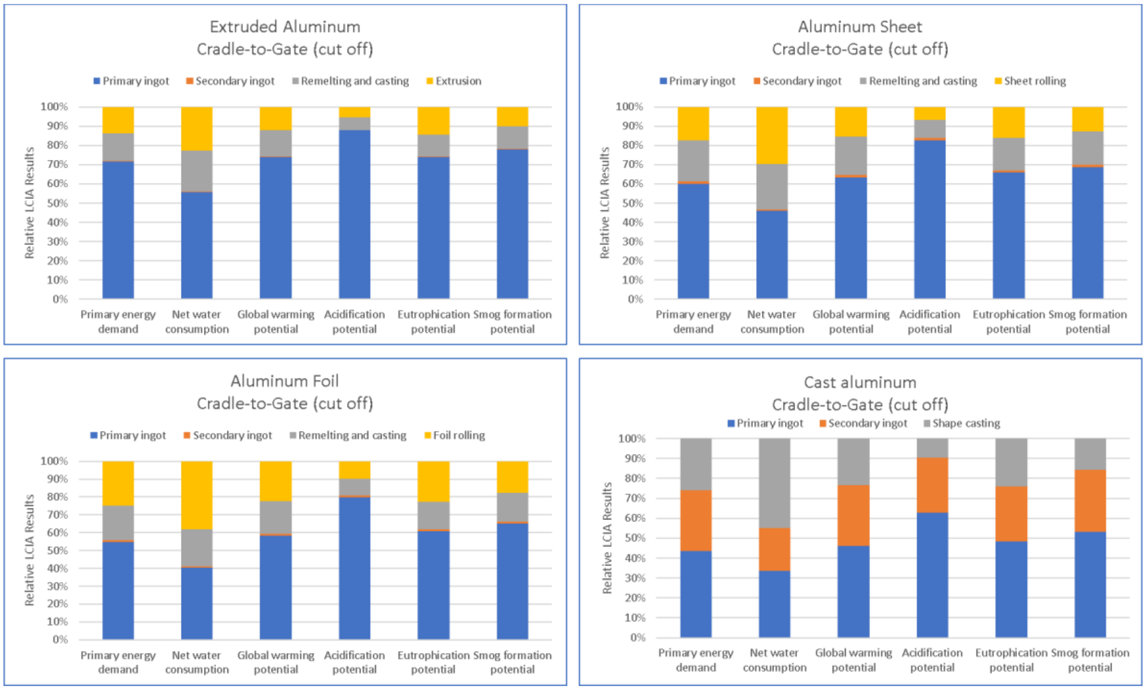

Figure 0-1: Breakdown of Cradle-to-Gate LCIA Results for extrusion, sheet, foil and die cast aluminum

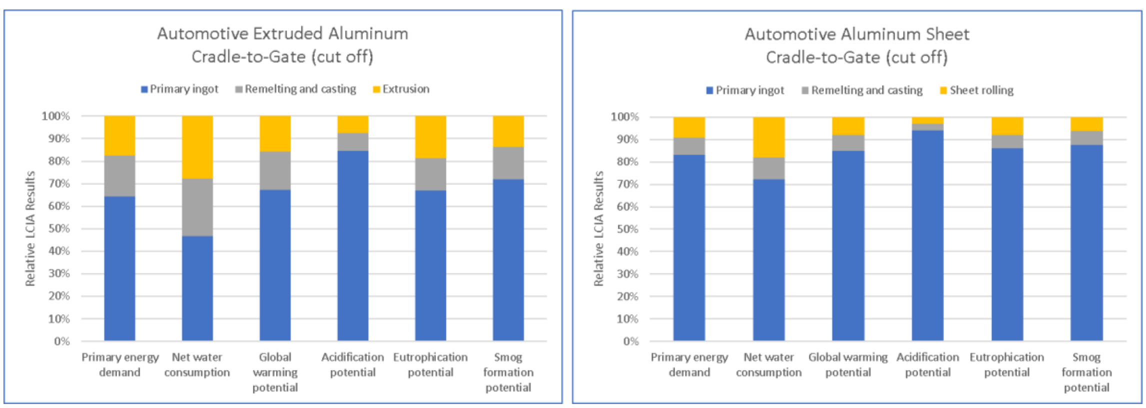

Figure 0-2: Breakdown of Cradle-to-Gate LCIA Results for automotive extrusion and sheet

0.2.2 Recycled Metal Reduces Footprint

Given the significant influence of primary aluminum on the cradle-to-gate footprint, **one way to address it is to reduce the use of primary aluminum and increase the use of recycled metal**. As shown in **Figure 0-3**, **a one percent increase in primary aluminum will increase the cradle-to-gate carbon footprint by as much as 117 kg CO2e for 1,000 kg of products. This is equal to say that a one percent increase in the use of recycled aluminum in the products will lead to a reduction of carbon footprint by the same amount.**

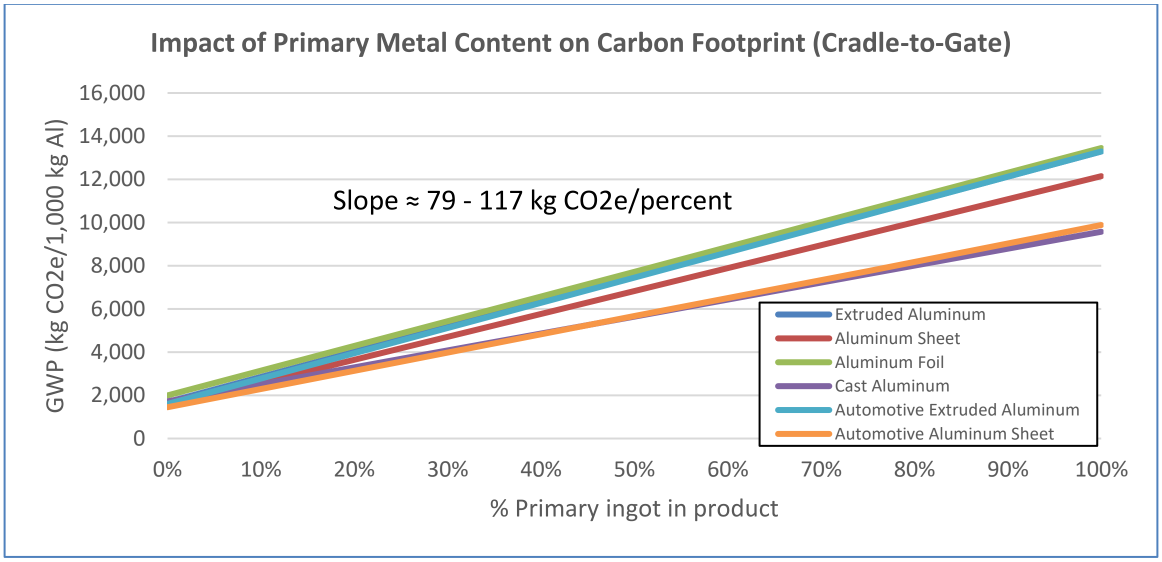

Figure 0-3: The impact of primary and recycled metal use on cradle-to-gate carbon footprint of semi-fab aluminum products

However, **the ability for manufacturers to increase the use of recycled aluminum is constrained by both resource availability and certain technical hurdles**. Aluminum scrap as a resource is limited by its availability since most scrap is from post-consumer products. **Most aluminum products have a very long lifetime in use**, particularly those in buildings, infrastructure facilities, transportation equipment and vehicles, and durable goods. Scrap can only be made available when a product is taken out of service and gets collected and recycled.

In addition to availability, scrap is often "contaminated" when it is collected and recycled in a mixed-material and mixed-alloy environment. In order for aluminum scrap to be effectively used to make a new product, the contamination must be removed by sorting, segregation and cleaning. **Current infrastructure in the recycling system is not good enough to efficiently and effectively segregate different materials and sort different alloys**. These technical hurdles need to be solved to achieve a true closed-loop recycling system for aluminum and other metal materials.

0.2.3 Not All Primary Aluminum Is Created Equal

Another way to achieve environmental impact reduction for manufacturers is to source cleaner primary aluminum. **Figure 0-4 shows the effects of primary aluminum sourcing on carbon footprint (cradle-to-gate), assuming the same level of primary and recycled metal contents in the products**. The regions and countries included in the sourcing analysis are:

- RNA represents the weighted average of the primary aluminum consumption mix in North America, which is the baseline case;
- CA represents Canada where primary aluminum is exclusively smelted with hydropower electricity;
- CN represents China where primary aluminum is mainly smelted with coal-fired electricity;

- RME represents the Middle East where primary aluminum is mainly smelted with natural gas fired electricity.

The scale of difference is dependent both on impact category (e.g., PED, GWP, etc.) and on how much primary/recycled aluminum content is in the products. The more primary aluminum is in the product, the more striking the difference between hydropower smelted aluminum and coal-power smelted aluminum. For instance, **the cradle-to-gate carbon footprint of automotive aluminum sheet made of Chinese primary aluminum would be *3.2 times* higher than it is made of Canadian primary aluminum when assuming the same primary aluminum content**.

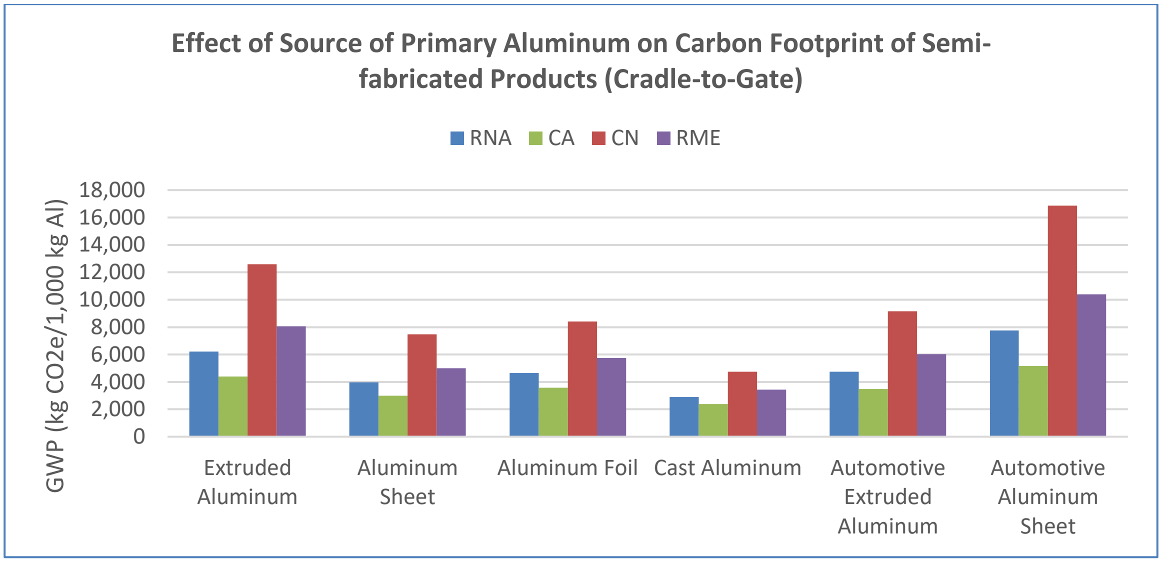

Figure 0-4: Effect of source of primary aluminum on Cradle-to-Gate carbon footprint. RNA: North America; CA: Canada; CN: China; RME: Middle East

0.3 Cradle-to-Grave

0.3.1 EOL Recycling Helps Significantly Reduce Footprints

From a ***cradle-to-grave*** perspective, the recycling of aluminum at the end of its useful life can significantly reduce the potential environmental impacts. The effect of increasing EOL recycling rates can be seen from **Figure 0-5**. The figure shows that **a one percent increase in EOL recycling can reduce the overall carbon footprint by 80 kg CO2e for 1,000 kg of products (or 0.08 kg CO2e/kg Al) for all examined product systems**. Similar effects can also be observed regarding to other impact indicators.

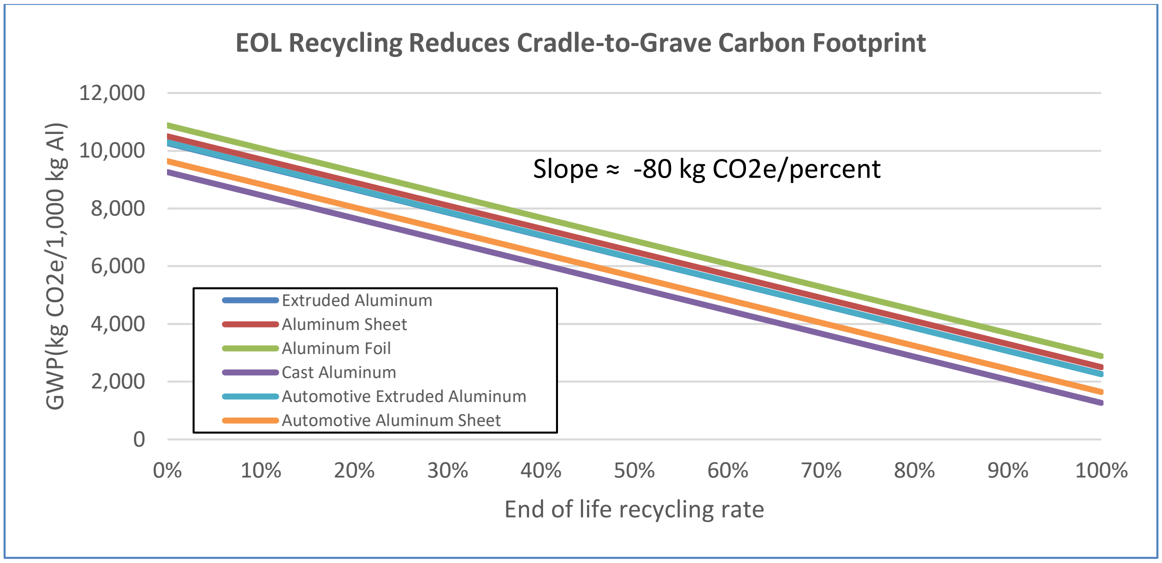

Figure 0-5: The impact of recycling on cradle-to-grave global warming potential of semi-fabricated aluminum products

The generic environmental benefit of recycling can be quantitatively calculated by comparing the cradle-to-gate primary energy demand and carbon footprint associated with primary metal production and the recycled metal production. **Figure 0-6** shows the results of such comparison. **Clearly, recycling aluminum saves *93 percent* of energy and reduces *94 percent* of carbon footprint compared to producing the metal from bauxite ore.**

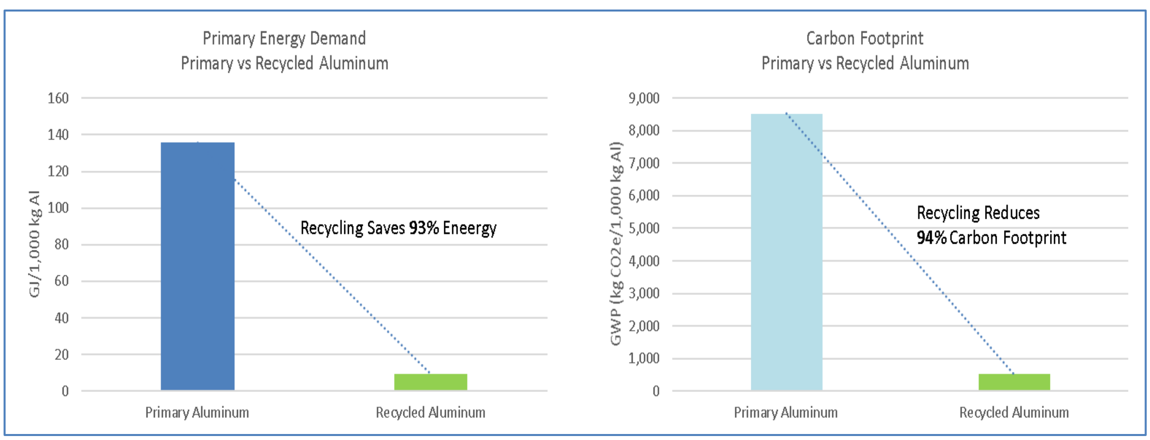

Figure 0-6: Energy savings and carbon footprint reduction associated with aluminum recycling

0.4 Significant Footprint Reductions Achieved

Progress can be measured by benchmarking with historical studies. During the past three decades, the Aluminum Association has sponsored numerous LCA studies. Many of them were either concentrated on assessing a particular product (1993, 2010 and 2014 studies) or product shipped to a particular market sector (1998 study), while others were focused on assessing generic semi-fabricated aluminum (2013 study). While the goal and scope of these studies have been somewhat different, it is still possible to extract information to document progress. For instance, all studies have covered primary aluminum and aluminum recycling in similar system boundary. This enables comparisons to identify trends for raw material production. In addition, the 2013 study is similar in scope and thus enables comparisons for some generic semi-fabricated products.

From ***a cradle-to-gate perspective***, **significant progress has been made in the North American aluminum industry in improving energy efficiency and reducing emissions**:

- For primary aluminum, energy demand and carbon footprint have been reduced **27 percent** and **49 percent** since 1991, respectively (**Figure 0-7**);
- For recycled aluminum, energy demand and carbon footprint have been reduced **49 percent** and **60 percent** since 1991, respectively (**Figure 0-8**)
- For generic semi-fabricated products, a similar downward trend can be seen regarding to energy demand and carbon footprint since 2010 (**Figure 0-9**)

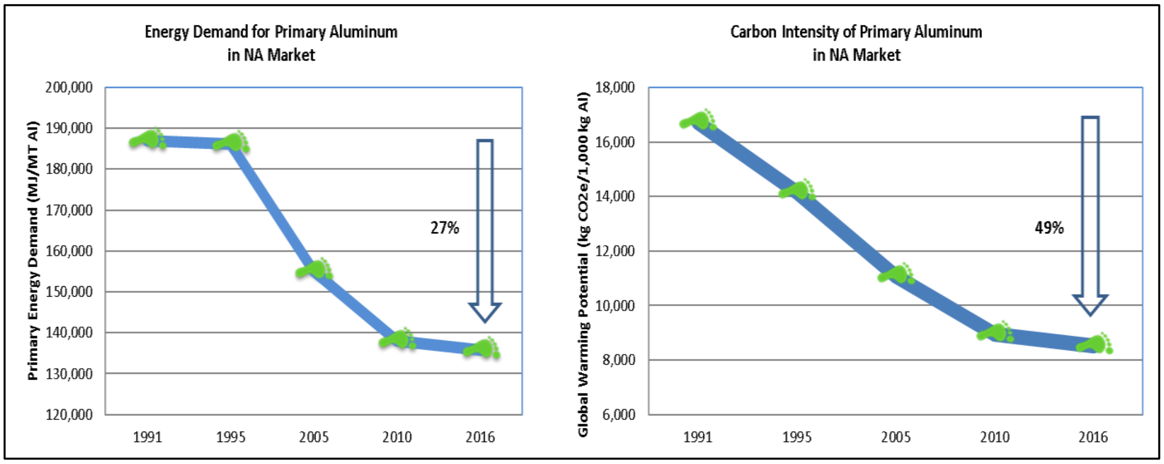

Figure 0-7: Trend of primary energy demand and carbon footprint associated with primary aluminum production

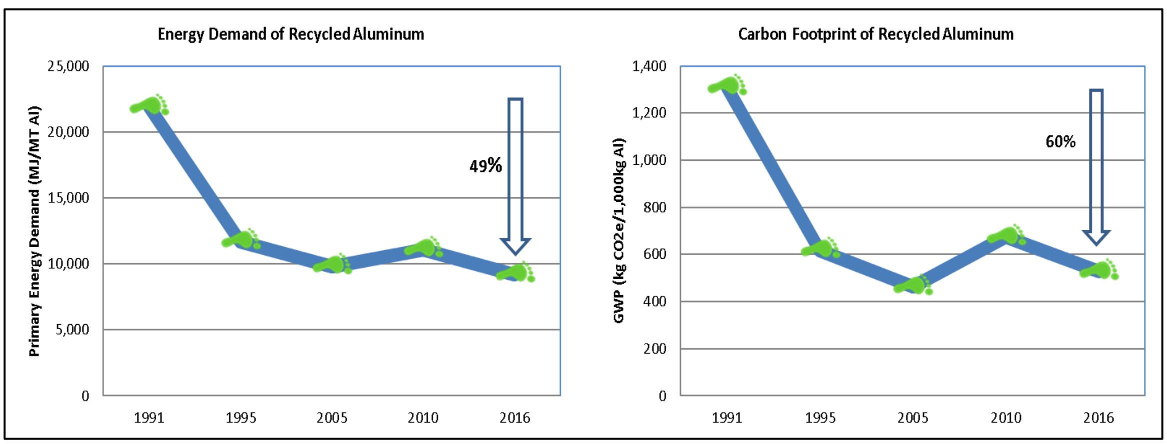

Figure 0-8: Trend of primary energy demand and carbon footprint associated with recycled aluminum

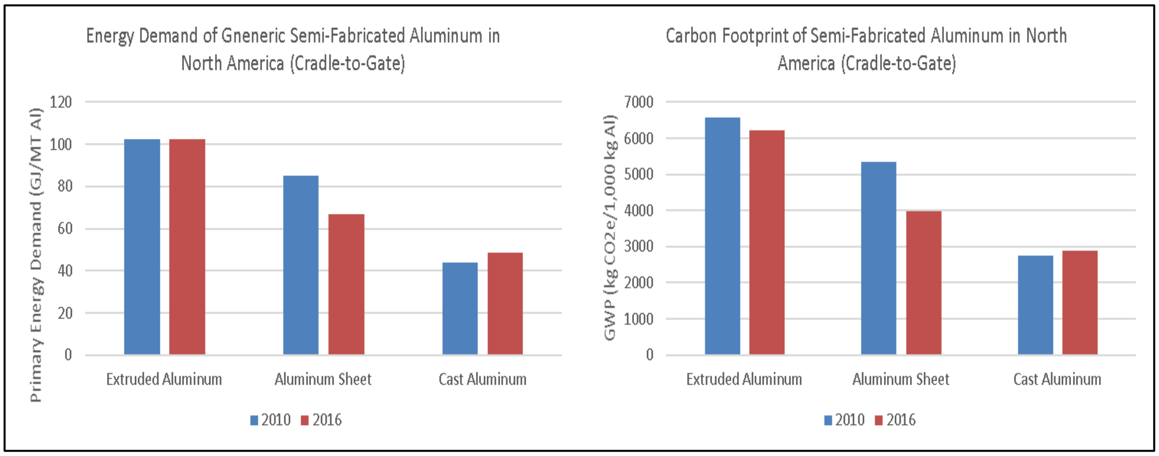

Figure 0-9: Trend of primary energy demand and carbon footprint associated with generic semi-fabricated aluminum (cradle-to-gate)

For *primary aluminum*, the improvement in energy efficiency and carbon footprint is partly attributed to technological progress in which computerized process controls have enabled less electric power consumption during the electrolysis process (**Figure 0-10**) and reduced greenhouse gas emissions such as CO_2 and perfluorocarbons (PFCs) (**Figure 0-11**).

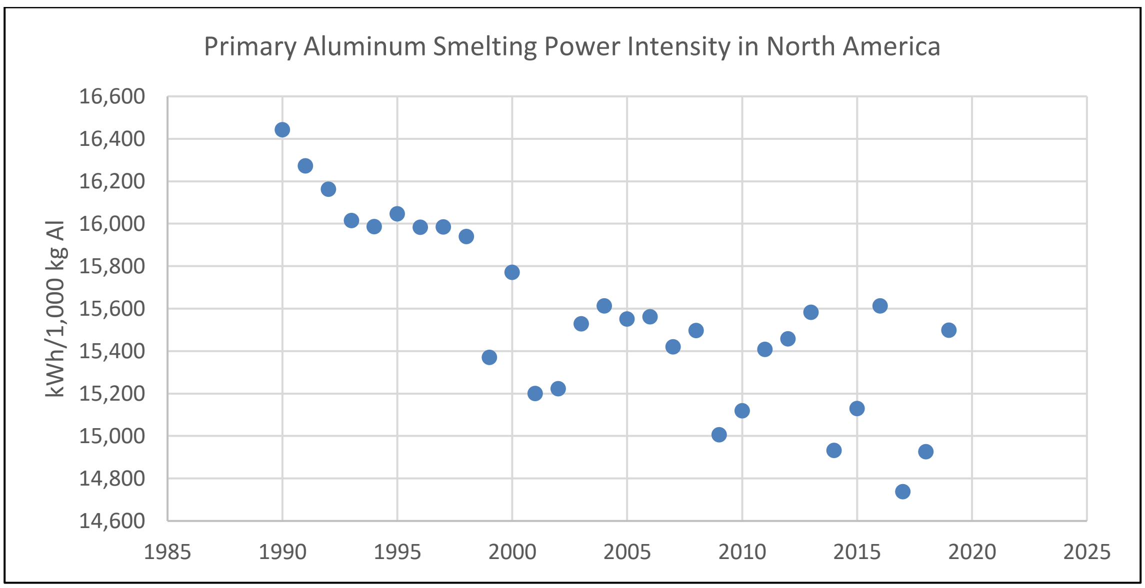

Figure 0-10: Trend of electric power consumption of primary aluminum smelting

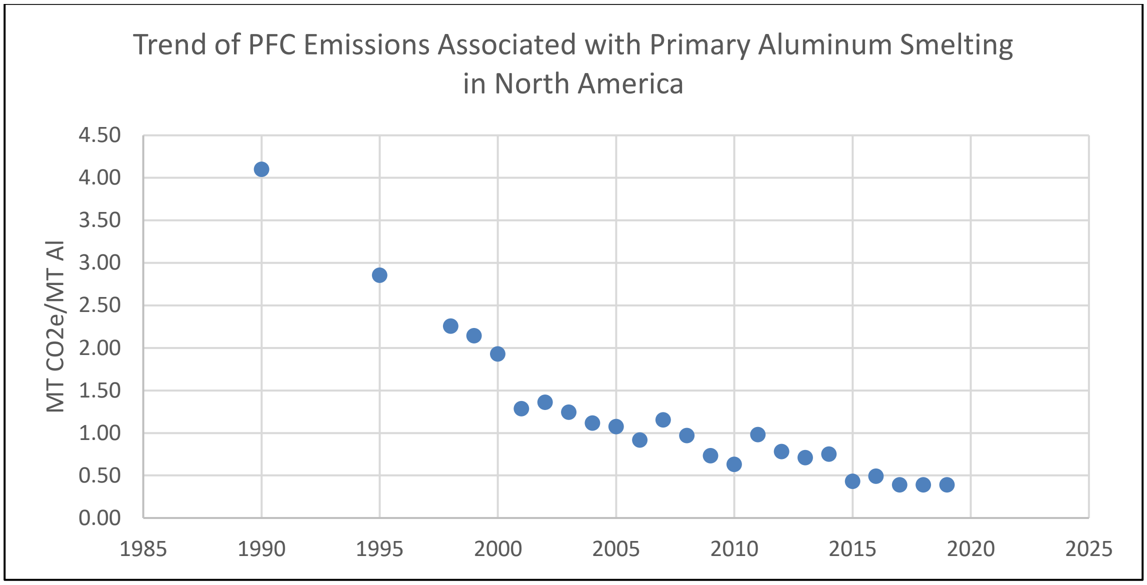

Figure 0-11: PFC emission intensity reductions

The improvement for primary aluminum 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 30 years, Söderberg facilities have been gradually closed and more pre-bake facilities have been built.

A third factor for the improvement for primary aluminum is attributed to the gradually increased share of renewable electricity and decreased share of coal fired electricity as an energy feedstock for smelting (**Figure 0-12**). This phenomenon is related in part to the phase out of Söderberg facilities which tend 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 and other renewable electricity.

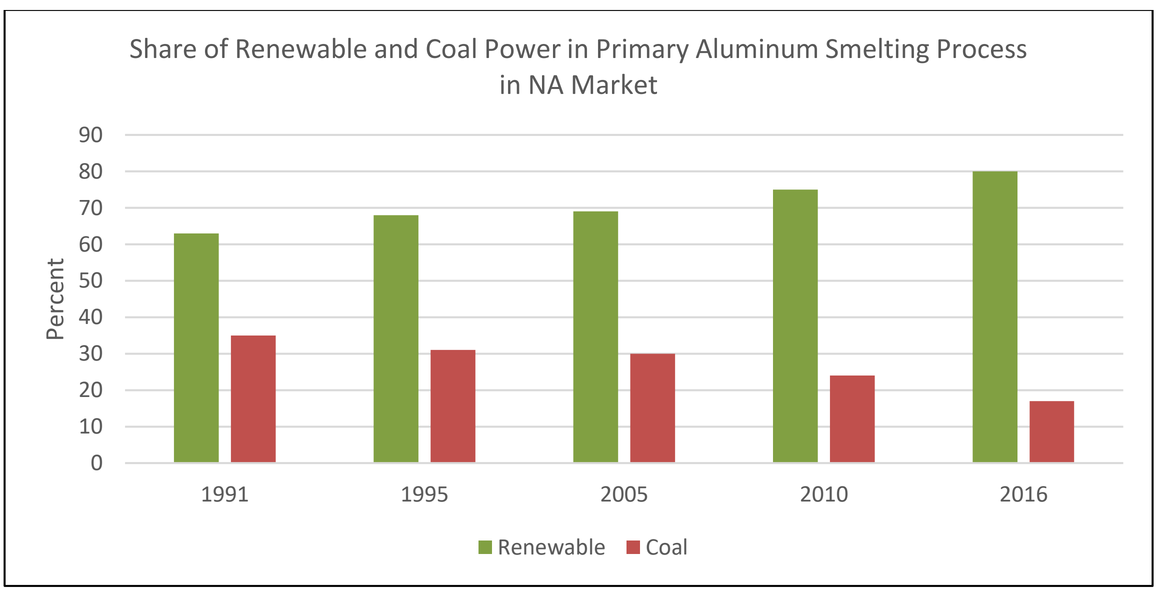

Figure 0-12: Relative shares of renewable (hydro and other renewable) and coal fired power for primary aluminum smelting in North America

For *recycled aluminum*, progress over the years can be mostly attributed to process efficiency improvement. Furnaces are more efficient today than 30 years ago. In addition, several other factors are likely contributing to the reductions in energy and carbon footprint as well. These include economies of scale (today's recycling facilities are larger than 30 years ago), scrap feedstock quality improvement (e.g., better sorting and better pre-treatment of scrap), variation in product forms for delivery (e.g., molten metal versus ingots), among others.

Improvement for *semi-fabricated products* is more complex since the cradle-to-gate footprint is not only related to production efficiency of the semi-fabrication processes themselves, but also to the footprints of primary and recycled metal, as well as the relative shares of primary versus recycled content. **For instance, both extrusion and sheet products have seen an improvement in energy demand and carbon footprint**. This is attributed to two major factors:

- improvement in the footprint of raw materials, and
- increase of recycled metal content (or decrease of primary metal content)

On the other hand, cast products have experienced an increase in footprint. **This is attributed to difference in production technologies assessed between the 2010 and 2016 productions**. The ultimate cause for the increase is due to the difference in recycled metal content:

- In the 2013 study (production year of 2010), cast product was represented by **sand casting** technology and average recycled metal content was ***85 percent***;
- In this study, however, the production is represented by **die casting** technology and average recycled metal content is assumed to be ***80 percent***.

0.5 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 cautioned against drawing 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 transportation, packaging, building & construction, and consumer durables. For example, the production phase of an automobile is as little as 10 percent of the total life cycle footprint while the rest is due to the energy consumptions during the use phase (Hottle, et al, 2017). Therefore, focusing solely on the production phase of a product like an automobile will lead to an incomplete environmental impact assessment and create unintended consequences.

Comparing to the production phase, the use phase is usually product specific and is not as straightforward. LCA practitioners should 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. **This study can be used as the foundation for data users to build their use phase upon it**.

0.6 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 beneficial use of aluminum and through improved quality of EOL recycling**.

As stated previously, the use of aluminum could substantially improve the overall environmental footprint of a product:

- Aluminum as a strong and lightweight automotive material can significantly reduce the energy consumption of the vehicles compared to both conventional auto steel and advanced high strength steel (AHSS), and thus help reduce the overall life cycle footprint of the vehicles (Audi, 2005; Dubreuil et al, 2010; Das 2014; Bushi et al, 2015; Bushi 2018;). An EPA literature review shows that "most of the LCAs reviewed demonstrated that aluminum-intensive designs were able to achieve the largest reductions in life-cycle energy use and GHG impacts, specifically in the use phase" (Hottle, et al, 2017).
- A study by ICF International concludes that depending on retail location, GHG emissions associated with the transportation and refrigeration of beverages packaged in aluminum cans are 8-23% lower than plastic bottles, and 67-90% lower than glass bottles (ICF, 2016).
- Studies by the European Aluminum Foil Association conclude that aluminum foil used for food and beverage packaging plays a key role in "minimizing the overall environmental impact of the product by reducing spoilage, over consumption, and/or by facilitating more sustainable lifestyles" (EAFA, 2008, 2009, 2010, 2011, 2013).
- Aluminum helps improve energy efficiency of a building. Strong, lightweight and durable aluminum products contribute to controlled and optimized functioning of heating, cooling, lighting, and ventilation systems. The optimization is achieved through balancing the competing needs of occupants in terms of optimal indoor temperature, maximum daylight and view, and maximum fresh air (AA Green Building Guide 2015).

Aluminum is a perfect material for recycling. When properly collected, sorted, and segregated, the recycling process does not change any functionality of the metal, regardless of how many times it is recycled. While aluminum products for transportation, infrastructure, building and construction, and durable goods have been historically mostly recycled at the end of life, the recycling rates for some consumer products such as packaging are far from expectation. It is estimated that a significant amount of aluminum, more than a million metric tons, is lost in landfills each year in the North American region. The recycling of these lost metals will not only help the industry reduce its environmental footprint, but also help society save the metals and the attached energy resources for future generations, thus achieving the ultimate goal of sustainable development for humanity.

Even for products with high recycling rates, the potential for improvement is still significant. The current recycling infrastructure available and technology deployed in

North America do not meet the demand for increasing the quality of recycling and closed-loop recycling of aluminum. Aluminum scrap collected is often mixed with other materials, and most harmfully, mixed with different alloys. Contamination of aluminum scrap by other materials and commingling of different aluminum alloys are common. Such contamination and commingling could lead to a phenomenon called “downcycling” – where high-quality wrought aluminum alloys end up being recycled into cast alloys since cast alloys have higher tolerance for impurity. While the metal does get recycled and reused, again and again for new products, such a system is not an optimal recycling system, and it does not reuse society’s scarce resources in the most efficient way. Most importantly, it is not sustainable since the demand for cast alloy has limitations.

To address this problem, we must work together to find better solutions. Policy makers need to develop smart and effective policies to incentivize quality recycling. The scrap collection industry needs to invest in new infrastructure to meet current and future demand. And technology developers need to seize the opportunity to provide state-of-the-art technologies to improve recycling efficiency and quality. The Aluminum Association calls on all stakeholders to work together to improve our aging recycling system to meet the 21st century demand for optimal use of our planet’s scarce resources.

1. Introduction

1.1 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 1-1**. This diagram displays only the interaction with the environment; the addition of economic and social systems further increases the complexity.

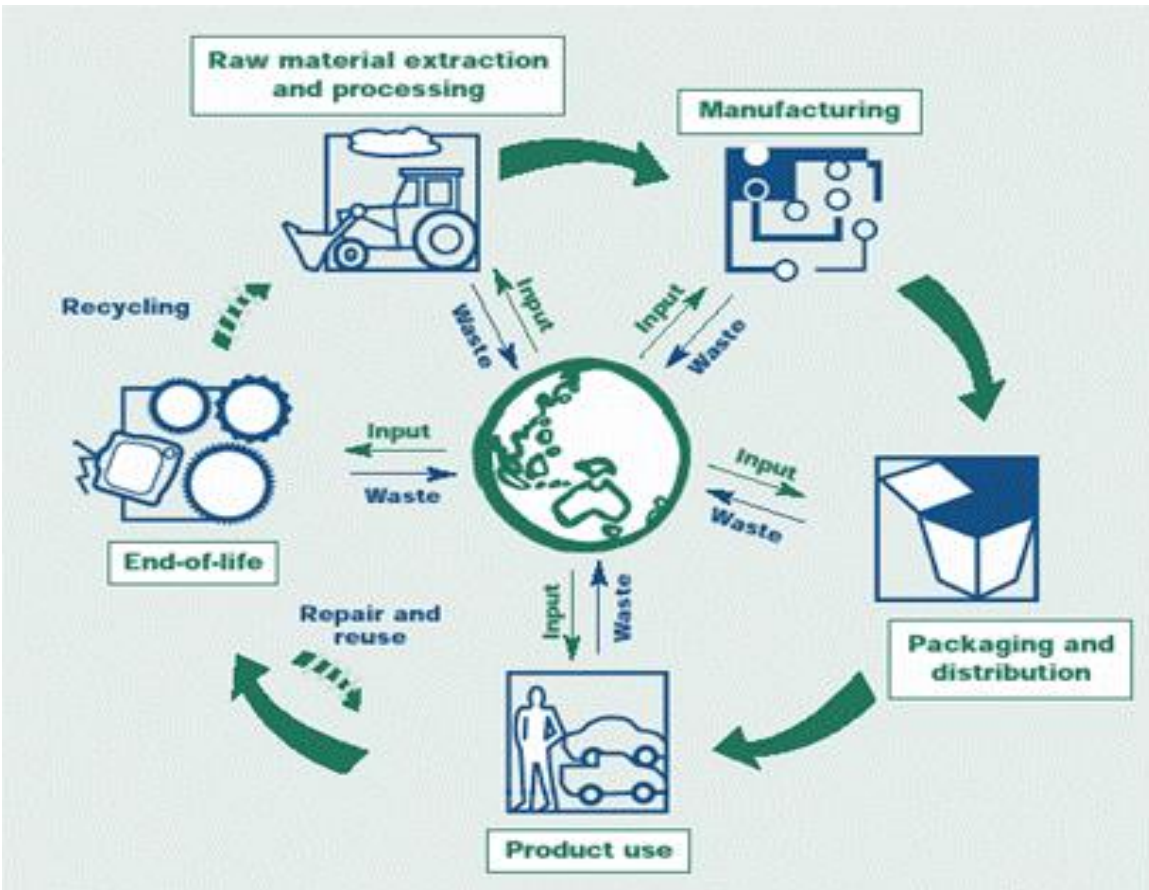

Figure 1-1: Product life cycle stages and the interactions with the environmental system (Source: UNEP 2005)

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 (EOL) management. "Life cycle approach avoids the issue of burden 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.

1.2 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 (i.e. cradle-to-grave). The goal of LCA is to quantify, evaluate, and then identify opportunities to reduce the overall environmental impacts 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 life cycle of a product or service, including the stages of resource extraction, manufacturing, distribution, use, recycling and ultimate disposal.
- Life Cycle Impact Assessment (LCIA) is the phase of LCA 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.

1.3 History of The Aluminum Association's LCA Studies

Although the Aluminum Association (AA) has sponsored many LCA studies during the past three decades, two of them were focused on assessing semi-fabricated aluminum products:

- The first study, carried out in 1996 and completed in 1998, examined the cradle-to-grave life-cycle inventory for automotive products (part fabrication, assembly and product use-phase were excluded). The baseline production year was 1995 (AA, 1998);

- The second, carried out in 2011 and completed in 2013, examined generic semi-fabricated aluminum products including extruded, flat-rolled and cast aluminum products. The baseline production year was 2010 (AA, 2013).

These LCA studies have helped the aluminum industry and its stakeholders understand in great detail about the generic semi-finished aluminum products and their average potential environmental impacts, enabling informed decision making and the identification of areas for improvements. Data generated by these studies has been disseminated to common global databases to enable stakeholders to conduct accurate assessments and make fair comparisons. The studies also helped the 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 of society by reuse and recycle products as much as possible.

1.4 About This Study

However, the aluminum product system is a dynamic one in which processes and technologies 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.

This study serves as an update of the 2013 report. The goal is to update all relevant datasets with newly collected data from facilities across North America. The baseline year of production information is 2016.

This report documents the processes and findings of the LCA update 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 allocation and data presentation methods
- A high-level analysis of the source of raw materials
- A life cycle inventory analysis
- A life cycle impact assessment, and
- Conclusion and interpretation

2. 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 2-1**:

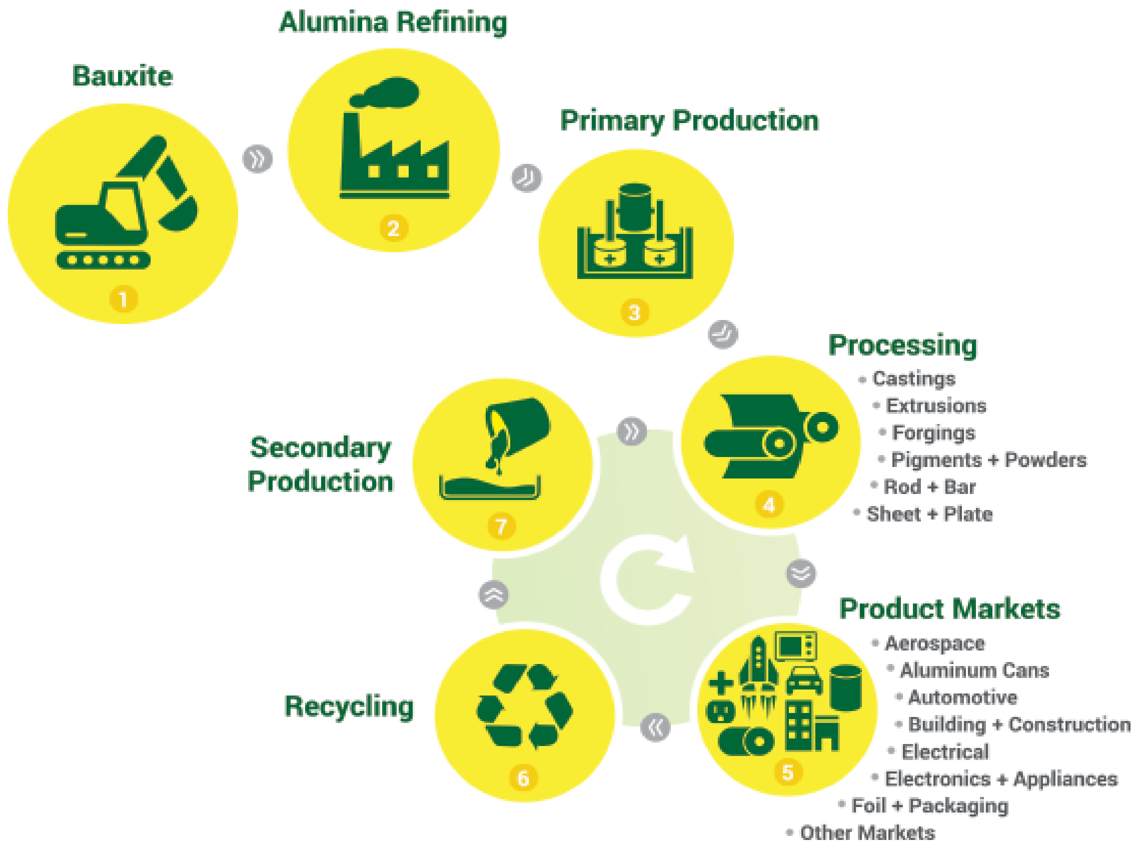

Figure 2-1: the life cycle of aluminum products

It is generally considered that the aluminum industry is the industry that involves in partial or all activities of the value chain except for "product markets" in which customers and end users play a key role. In North America, the industry involves mainly in metal production, processing (semi-fabrication), and recycling.

There are two distinctive routes of aluminum raw metal 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. When an aluminum alloy is made into specifications with either of the resources, no chemical testing can tell which source of raw material has been used. 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 (service life) can be as short as a couple of months, or it can be as long as a century. At the end of the product's life, it is usually recycled into new metals, or in some cases disposed into landfills.

The Aluminum Association

Most of the environmental burdens of aluminum product manufacturing 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 small compared to the total life cycle burdens. Finally, at the end-of-life stage, if the metal is reused or recycled into new metal to make the next generation of products, almost all environmental burdens would be saved through the avoidance of producing additional virgin metal. If the metal is discarded and end up in landfill, all "investments" will be lost along with the material.

3. Goal and Scope Definition

3.1 Goal of the Study

The primary purpose of the study is to update a 2013 semi-fabricated aluminum product LCA that includes all major categories of generic semi-fabricated aluminum products (extruded, rolled, and casted). These products are 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 LCIA information that can be used to conduct all purpose of LCAs for consumer products involving relevant aluminum components.

Such update is necessary as the previous data became increasingly out of date due to changes occurred in the supply chain and energy profile, technological progress, and efficiency improvements. The updated data and information shall reflect the current technological situation, production practices, as well as the average North American market situation.

With such an update, the Aluminum Association and its member companies can assist stakeholders to better understand the environmental implications of manufacturing with aluminum. At the same time, the data will help the industry identify potential areas for improvements. Such an evolutionary process of understanding – identification – improvement is a fundamental commitment of the industry in its sustainability movements.

3.2 Intended Audience

The intended audience for this study is the Aluminum Association itself, aluminum manufacturers and their customers, aluminum value chain stakeholders, LCA professionals and practitioners, academic researchers, policy makers, as well as the general public. The Association will use the information from this study in an aggregated manner for public communications, to develop marketing materials, and to provide data to stakeholders for the purpose of conducting LCAs within their own applications.

3.3 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 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 design options (for instance, alternative process design, technology, etc.), compare corresponding datasets (benchmarking), and guide the evaluation of modifications for improvement;
- Provide information for use in strategic planning and sustainable development; and
- Develop communication messages such as Carbon Footprint of Products (CFPs), Environmental Product Declarations (EPDs), and industry sustainability reports.

3.4 Limitations for Use

Life cycle assessment is a modeled approach based on specific assumptions. The Aluminum Association recognizes the potential for misuse of LCA data and information by users. **For instance, there have been cases in which competing material industries use carbon footprint associated with per kilogram of primary aluminum to compare with that of a kilogram of another material to establish claims for environmental "superiority" of their own materials.** Such misuse is not only detrimental to the aluminum industry, but also highly misleading for the public.

Therefore, it is noted here that the updated inventory data 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.

3.5 Product Systems under Study

The product system under study is the enclosed life cycle stages and processes in **Figure 3-1**. 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 this study are:

- Primary metal
- Recycled/secondary metal
- Rolled products including automotive sheet, generic sheet and plate for building and consumer durable applications, and foil. Excluded in this study is can sheet which is part of an independent beverage can LCA (AA, 2021)
- Extruded products including automotive extrusions and extrusions for other applications
- Cast products represented by die casting

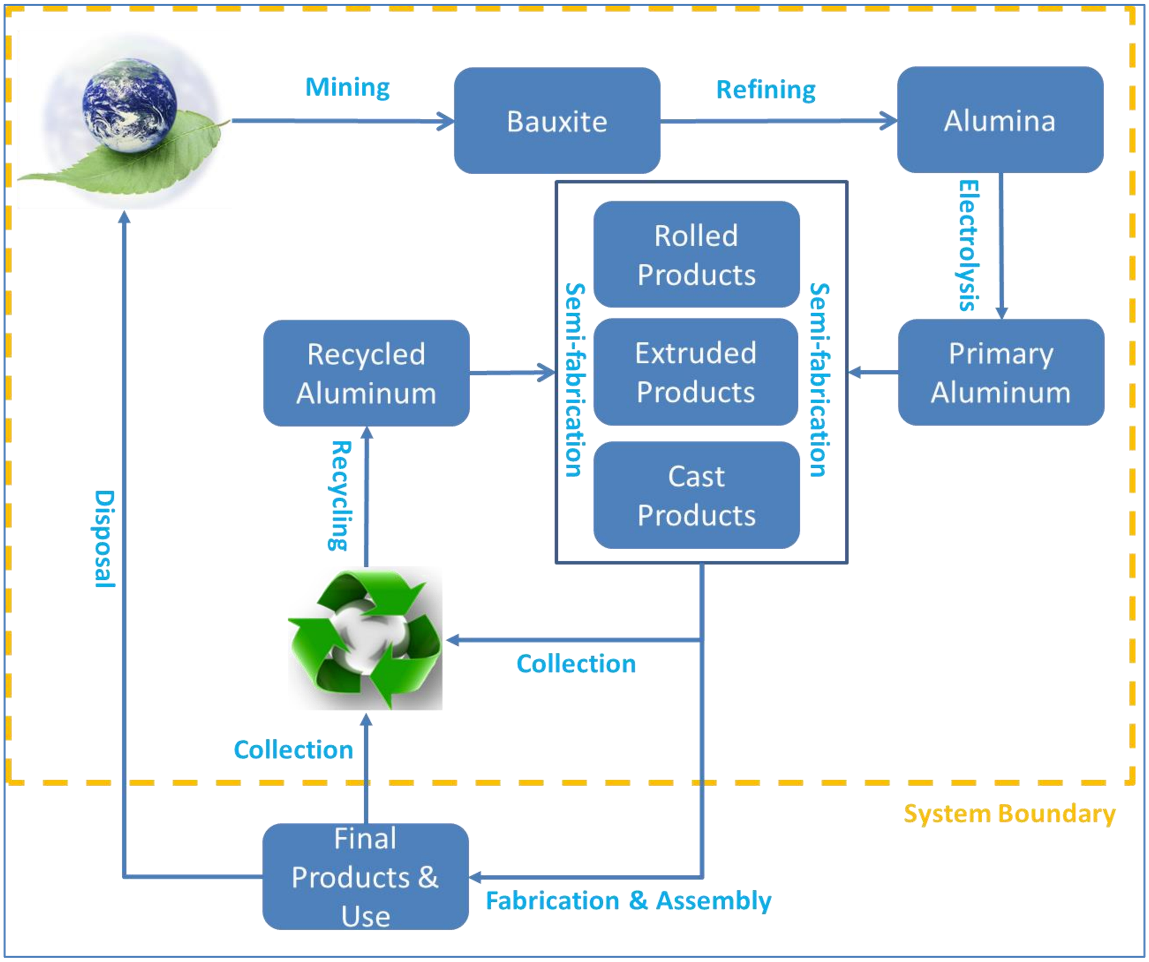

Figure 3-1: life cycle stages included in this study.

3.6 System Boundaries

The products being examined are semi-fabricated aluminum products. The physical properties of these products, their manufacturing and impact represent the current technological situation in the North American market. The products may be further processed and assembled before use, but those activities are not included in this study. The system boundaries are summed in **Table 3-1**:

Table 3-1: Summary of system boundaries

Included	Excluded
• Raw materials extraction • Energy and fuel inputs • Extraction, processing and delivery of energy and fuel inputs • Extraction and processing of auxiliary materials (e.g. chemicals, solvents, lubricants, packaging etc.) • Production of metal and processing it	• Capital equipment and maintenance • Maintenance of equipment • Human labor • Pre-use fabrication and assembly • Use of product

into semi-fabricated products • Product surface treatment and finishing (e.g. anodizing, coating etc.), if it's reported by data providers • Transportation of raw and processed materials and products • Recycling • Waste treatment and disposal • Overhead (heating, lighting) of manufacturing facilities	

3.7 System Function and Functional Unit

The function of the products is to serve as individual components, parts, units, or integrated systems to be used for transportation, building and construction, packaging (in the case of foil), durable goods, or other markets and purposes.

The functional unit for this study is to model for **1,000 kilograms (one metric ton)** of aluminum products.

3.8 Geographic Coverage

The geographic coverage is **North America including Canada and the United States**. Excluded in geographic coverage is Mexico since no company from Mexico participated in the study.

Specific geographic coverage of individual production processes is summed in **Table 3-2**:

Table 3-2: 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, other countries or regions where metals were imported from
	Electricity Generation	For the smelting and ingot casting processes, it is the aluminum industry specific power mix based on power contracts and captive power capacities, representing all smelters in Canada and USA, as well as countries that have net export of non-alloyed primary aluminum to North America; for other processes, it is the average grid mix of the relevant production country or region.
Recycled Metal Production/Recycling	Scrap Collection and Processing	North America
	Metal Production	North America

	Electricity Generation	Average U.S. grid mix is used since majority of production is in the USA.
Semi-Fabrication	Ingot or billet casting	North America
	Extrusion	North America
	Rolling	North America
	Die Casting	North America
	Electricity Generation	Specific power source of most individual facilities can not be tracked. Average U.S. gird mix is used since majority of production is in the USA.

3.9 Temporal Coverage

The designated temporal coverage for this study is the production year of 2016. Primary data collected from the participating companies and for their operational activities are representative for the calendar year of 2016 (reference year). Additional data necessary to model raw material production and energy generation, etc. were adopted from the database of the GaBi software. The temporal coverage of these datasets is dependent on what's available in the latest version. The general criteria for data selection are to use the latest data.

It is worth to mention that some companies reported operational data that is different from the reference year, depending on the timing of their report submissions and the convenience of data availability. The variations included production years of 2015, 2017 and 2018.

Special note is made for data for automotive extrusion and automotive sheet products. Data used to model these products is a result of a combination of data from two separate surveys: the original LCA survey on generic extrusion and generic sheet productions, and a supplemental survey on raw material inputs for automotive sheet and automotive extrusion productions. Data reported by producers for the supplemental survey covers the production year of 2018 for automotive extrusion, and the production year of 2019 for automotive sheet.

Overall, the consequence of deviation of data from the defined reference year is considered minor because there have been no radical changes observed in the industry regarding to production technology, operational practice, and raw material sourcing for most examined products during the period of 2015 to 2019.

An exception is automotive sheet production. This is a rapidly growing market over the past several years. While the production technology remains the same over the period, the scale of production has increased significantly, and the sourcing of raw materials has also evolved rapidly. Increase in the scale of production has resulted in efficiency improvement. And the evolution of raw material sourcing has enabled more input of scrap material and less input of primary metal. Data users should keep in mind that this trend will continue, and the production year of 2019 is the latest period in which data is available.

3.10 Technology Coverage

The study covers the currently operational technology mix for aluminum metal production and semi-fabrication. The representation of each specific technology is reflected in the weighting factor of the manufacturing facility/facilities representing the technology within each product category. Weighting factor is determined by the share of the facility/facilities in production volume within that category.

4. Data Collection, Software, and Database

4.1 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 reported by manufacturing facilities is preferred to secondary and tertiary source data. In collecting primary operational data, several steps were carried out to achieve a predetermined objective of high-quality data representing the industry in its current manufacturing performance.

4.1.1 Data Collection Procedures

Data collection for this LCA was a globally coordinated effort within the aluminum industry, carried out by the Aluminum Association and the International Aluminium Institute (IAI).

The first step was to decide which organization is responsible for collecting data for what 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 life cycle stages, data for raw material extraction and primary metal production was collected by IAI. The London based trade association regularly collects data and information from bauxite mining companies, alumina refining facilities and primary aluminum production facilities across the globe, including all North American facilities. Aggregated datasets representing North America was directly transferred to the Aluminum Association upon request.
- Data of secondary aluminum production, semi-fabrication, and recycling was directly collected by the Aluminum Association from relevant manufacturing facilities in the North American region.

The second step was to look into the Aluminum Association's database, known as the Aluminum Buyer's Guide, to identify survey targets in the region. Due to the large number of manufacturers and facilities involved, it was essentially impractical as well as unnecessary to collect data from all players.

For this reason, the third step was to select survey samples from the entire database of producers. Based on past experiences in such data survey, efforts were focused on member companies of the Aluminum Association. These companies represent at least 80 percent of the capacity in the region, and the sizes of these companies also represent well of the industry.

The fourth step was to conduct survey. This included survey form distribution, response collection, data quality checking, and data aggregation. **This was the longest and most onerous step of the entire project. Due to the large and diversified sample size, it took three years to complete this step, ending up with appropriate response rates (refer to section 4.1.4) to represent the industry in the region.**

Nevertheless, survey on aluminum casting (foundry) ended up with failure and there was not enough response to represent the industry. For this reason, third party data from the GaBi database was chosen to model the aluminum **die casting only**.

4.1.2 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 4-1**:

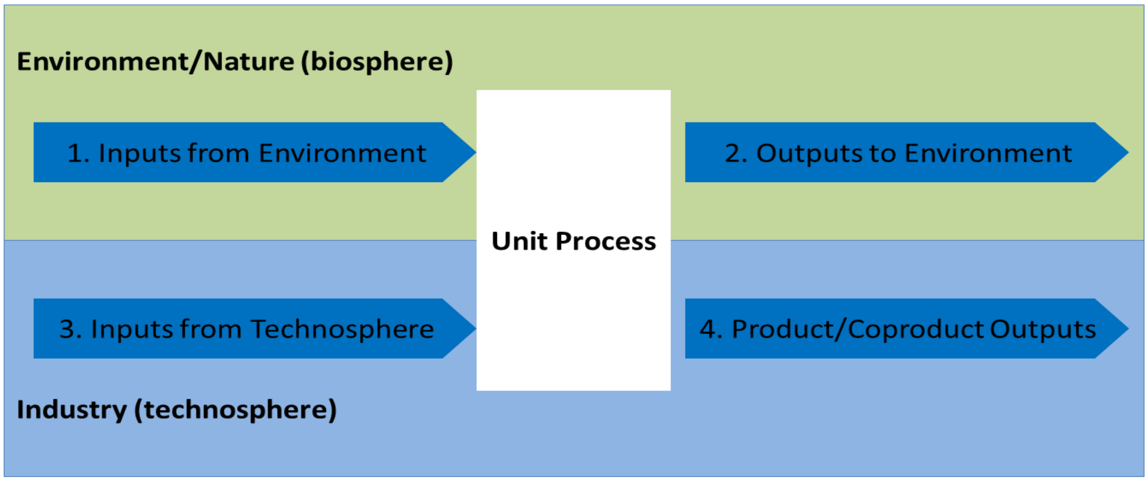

Figure 4-1: Life Cycle Inventory – Unit Production Process Template

In particular, the following data categories were 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 ancillary material inputs
- Product, intermediate product, and by-product outputs
- Environmental releases including air, water, soil, and solid waste releases
- Waste treatment mechanism (e.g. treated, non-treated, recycled, landfilled, etc.)

In addition, data categories such as plant information, definition of terminology, and process chart were included in the survey forms. These additional information categories were 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 was put on finding out the nature/source of metals used for semi-fabrication. In doing so, the raw material input category was specifically designed to track metal feedstock at the point of cast house where ingots for semi-fabrication are produced. For instance, the rolling survey included the following categories of major material inputs for the remelting & ingot casting process:

- Processed old/postconsumer aluminum scrap, if any

- Processed new/pre-consumer aluminum scrap, if any
- Processed mixed aluminum scrap (commingle scrap with source non-identifiable), if any
- Processed internal/run-around aluminum scrap, if any
- Molten/liquid primary aluminum (hot metal from electrolysis pots), if any
- Molten/liquid recycled aluminum (hot metal from remelting furnaces), if any
- Primary aluminum sow or ingot, if any
- Recycled aluminum ingot, if any
- Other aluminum ingot (specify)
- Alloy elements, if any

4.1.3 Format of Survey

Survey forms were in EXCEL spreadsheets for learning purposes. Such learning experience is essential both for the Aluminum Association and the participating companies and plants. 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 secured email systems.

4.1.4 Response Rate and Overall Coverage

As a result, more than 90 plants representing 19 companies responded the survey and provided data. This level of response, in terms of total outputs from reporting facilities as a percentage of total productions in each product category, represents the following industry coverage (**Table 4-1**):

Table 4-1: Estimated industry representation by product categories

Product Categories	Industry Representation (Percent)
Primary Metal (for NA domestic production)	92
Recycled Metal by Independent Recyclers (excluding recycled metal production by integrated mill producers)	80
Extrusion Products	40
Extrusion Products for Automotive	70
Sheet and Plate	79
Sheet for Automotive	90
Foil	35
Die Cast Products	N/A

Note: coverage for automotive sheet and automotive extrusion is represented by responses to the raw material input (recycled content) survey

It is important to point out that the coverage in each of the categories is defined as the cumulative tonnage of productions reported by the reporting facilities as the percentage of the total producer shipments by the industry (statistical shipments). This definition of coverage and its calculation may be different from practices by other industries.

4.1.5 List of Survey Respondents

A list of survey respondents is provided in **Appendix 12.1**. The list is in alphabetic order by company names. This list is provided for the purpose of verifying individual company's participation for industry environmental product declarations based on this LCA. Some of the companies have gone through merger and acquisition (M&A) since the completion of the data survey. For that matter, the list reflects the latest parent company names after the M&A. For instance, part of the businesses of the formal Aleris Inc. has been acquired by Novelis, and the remainder is now Commonwealth Rolled Products.

Special attention shall be put that only names of the parent companies have been listed. Subsidiary companies belonging to these parent companies should be automatically covered by this study. For instance, Kawneer is a subsidiary of Arconic Corporation. All facilities of Kawneer provided data for the study and therefore shall be covered.

For most of the listed companies, all of their relevant production facilities in the United States and Canada participated in the survey. Only a small fraction of the listed companies did not have full participation by all production plants. This was allowed to encourage participation by non-member companies of the Aluminum Association.

4.2 Software and Database

There are additional critical ancillary materials and production processes that are outside of the aluminum industry. **These include the production or processing of all relevant ancillary materials; the production of fossil and non-fossil fuels; the generation and transmission of electricity; road, marine and air transportation; waste treatment and disposal; among others.** Also as stated previously, the survey of aluminum casting/foundry companies, although considered part of the aluminum industry, failed to generate any meaningful data due to a variety of reasons. Therefore, appropriate database is needed for LCI information for these materials and processes. 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.

4.3 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 for each product systems.

4.3.1 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) or gigajoules (GJ). 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.

Fuel (fossil or non-fossil) inputs 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) published by the Energy Information Agency (EIA). In some cases, the conversion was done by the GaBi software. The resulted primary energy demand was presented as net heating value.

4.3.2 Aggregation, Integration and Averaging

Given the confidentiality 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, survey data concerning the same product or process were aggregated, averaged, and presented in a fashion that ensures confidentiality of individual company's information. The aggregated results (weighted-average numbers normalized for each unit production process) were sent to the LCI model developer (Sphera) to calculate life cycle inventory and perform 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's 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 only send to a 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. In principal, the vertical method (see **Figure 4-2**) was applied consistently to all the companies as this method is more representative of actual industrial processes.

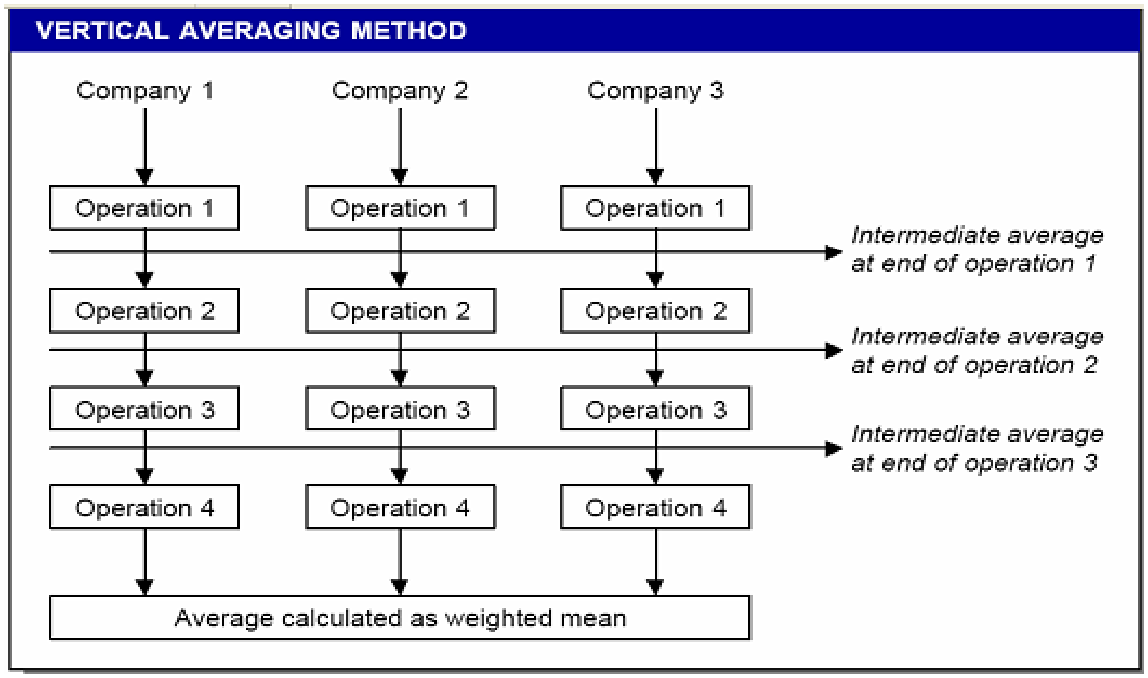

Figure 4-2: Illustration of the Vertical averaging method (ECOBILAN, 2001).

However, in the case of identical processes in which certain data reporting is missing from a particular facility, the horizontal averaging method (see **Figure 4-3**) 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.

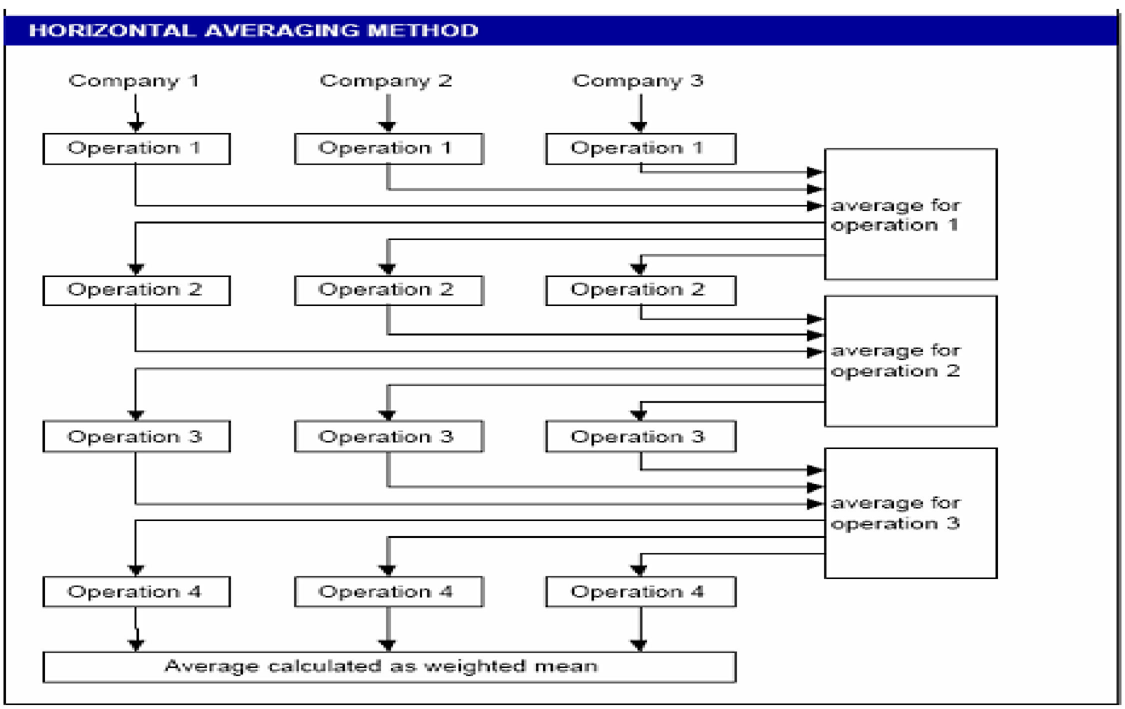

Figure 4-3: Illustration of the Horizontal averaging method (ECOBILAN, 2001).

4.3.3 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 ingots or semi-products.

The end-of-life allocation was done by taking a ***substitution – net scrap approach***. Detailed explanation of the allocation method is given in **Section 5.1**.

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 models and the energy input is reduced accordingly. In any case, such energy input from incineration is very limited (less than 0.01%).

4.3.4 Cut-Off Criteria

The following cut-off criteria were used to ensure that all relevant environmental impacts were represented in the study. It is worth to note that such cut-off, if happens, was largely done during the primary survey data aggregation process. And it was carried out through rough estimations:

- 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.

4.3.5 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 12.2**.

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 did not exceed 5% of the total reported data points.

4.3.6 Treatment of alloy elements

Most aluminum products are in the form of alloys. Aluminum alloys are divided into wrought and cast alloys. Within each category, there are also multiple groups and subgroups represented by different designation codes. Common alloy elements include copper, iron, magnesium, manganese, silicon, zinc, etc. Together, alloy elements have a share of 1 – 15 percent of the total weight of aluminum products, depending on the alloy groups.

Instead of incorporating data of all relevant elements into the LCA models, this study – as with all past studies – replaced all newly added alloy elements (note: aluminum scrap itself contains alloy elements) with primary aluminum. Such a treatment simplifies the models. Meanwhile, it also prevents undercounting of the environmental footprint of the products.

There are four major considerations for such a treatment. The first consideration is that there is a great variety of alloys and – with the generic products of semi-fabricated aluminum being the focus of this study – the exact alloy elements and their respective quantity can not be determined. The second consideration is that the proportion of alloy elements is small in most cases particularly for wrought products, which is the majority of the North American industry production. The third consideration is the barrier for data reporting. Facilities do report the total quantities of their overall alloy element consumptions during the data survey. However, they would not report the specific names of those elements and their respective quantities since that's the proprietary business information. Lastly, substituting alloy elements with primary aluminum does not end up with under-counting of the potential environmental impact since on a per unit mass basis, the footprint of primary aluminum is often higher than most of the alloy elements. The substitution is a conservative approach.

4.4 Division of Tasks and Responsibilities among Involved Parties

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

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.

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

4.5 Critical Review

The results of the LCA study are intended to support external communication. Although not mandatory by ISO 14044 in the absence of a comparative study, a critical review of the study was still 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 Technical Working Group (STWG) of the Aluminum Association and an independent review panel. The STWG is comprised of the following members:

- Jessica Sanderson, Chair of the STWG, Novelis
- Alison Conroy, Novelis
- Olivier Neel, Constellium
- Jerome Fourmann, Rio Tinto
- Rajini Janardhan, Rio Tinto
- Anthony Tufour, Arconic
- Stig Tjotta, Hydro Metals
- Laura Coleman, Alcoa
- Kenneth Martchek, Martchek Consulting.

Members of the independent review panel were invited by the Aluminum Association. Such a review process shall also be valid for the verification process for Environmental Product Declarations. Members of the review panel are:

- Stephanie Carlisle, University of Washington
- Yuan Yao, Yale University

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.

5. Methodology for Recycling Allocation and Data Presentation

5.1 Methodology

The study is both a life cycle inventory analysis and a life cycle impact assessment. As a result of the study, “cradle-to-gate” LCI and LCIA information is provided for major intermediate and final product systems starting with the extraction of bauxite ore at the mines, or scrap collection at various generation sites, and ending with fabricated products at the factory gate.

In addition, “cradle-to-grave” (excluding product finishing, assembly, and use phases) LCIA results are provided for each of the final product systems under the study, starting with resource extraction and ending with the recovery and recycling of end-of-life scrap. The baseline EOL recycling rate is assumed to be 95 percent for all products. The assumption is arbitrary for simplicity.

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

5.1.1 Allocation for EOL Recycling

Allocation is to strike a “fair-share” for the inputs and outputs related to a production process. When a process produces multiple useful products, the role of allocation is to assign input resources and environmental releases to each of the products in a manner that reflects a certain scientific rationale. The most common situation for allocation is when co-products are produced together with the product under study. For this study, there are no major coproducts during the aluminum product manufacturing processes. The focus for allocation is on EOL recycling.

Allocation in LCA is governed by ISO 14044, section 4.3.4 (ISO 14044, 2006). However, the language in Section 4.3.4. is highly generic and it only defines general principals for allocation, including avoiding allocation if possible. This is due to the nature of highly individualized circumstances for a particular product or a manufacturing process. There is no such thing as a one-size-fits-all solution for allocation.

The goal of allocation for recycling is to divide inputs and outputs and hence, environmental impacts between the product system that generates scrap and the product system that utilizes scrap. The two product systems may be the same (“closed-loop”) or they may be different (“open-loop”). The reason for allocating the inputs and outputs between the two is that recycling helps recover materials and preserve scarce resources.

It is important to emphasize that the scrap for recycling may be new (pre-consumer scrap) or old (postconsumer scrap). Taking a unified allocation approach for both new and old scrap recycling is a more practical solution than treating them differently if the scrap has the same inherent chemical properties. For aluminum products made of the same alloy and processed with the same fabrication technique, new and old scrap do have the same chemical properties since they originated from the same piece of metal. The only difference is the time of availability – new scrap can be available for recovery and reuse immediately and old scrap can only be available for recovery and reuse when the product reaches its end of service life. A unified allocation approach for new and old scrap recycling reflects the fundamental thinking and practice of an integral, systemic, and full life cycle of a product.

Historically, there are two main allocation approaches for EOL recycling. One is known as "cut-off", "recycled content method", or "100:0 method". Another is known as "substitution", "avoided-burden", "end-of-life recycling method", or "0:100 method". Recent literature pointed out that for an attributional LCA, the term "avoided-burden" is not appropriate. Instead, "avoided-burden" shall be explicitly used for consequential LCA, and "substitution" is the right term for attributional LCA (Koffler, 2017).

To make the matter more complex, there are also hybrid approaches that are a combination of the two main methods. The development of such allocation approaches is to address the environmental concerns people have about the two main methods. The top environmental concern about a pure cut-off method is that it is strong in incentivizing the use of recycled material but weak in promoting postconsumer recycling. On the other hand, the concern for a pure substitution method is that it may encourage postconsumer recycling but is weak in incentivizing the use of recycled material for products. If recycled material is not used, it would be useless to recycle and it would not serve to promote a circular economy. In addition, if the product takes a long time to be available for recycling and if the real recycling rate does not meet with the expectation (since most of the EOL recycling rates applied in LCAs are either based on pure assumptions or today's observed rates instead of the reality of the future), a substitution approach would be neither practical nor matching the reality. Finally, it is not easy to be accepted by certain market sectors such as building and construction for taking credit today for the recycling of materials that will eventually happen decades later in the future (Frischknecht, 2010; Koffler, et al, 2017; McMillian, et al, 2012, Vadenbo et al. 2016).

A **Net Scrap Substitution Approach** has been taken to calculate the cradle-to-grave LCIA in this study. **This approach in essence is a hybrid of both cut-off and substitution** in that it does not assign any upstream burden to scrap used in manufacturing, like the cut-off approach, but instead applies a substitution approach to the net amount of scrap collected for recycling over the entire life cycle. The application of the net scrap substitution approach can be reflected in ISO 21930, clause 7.2.6 and EN 15804, clause 6.4.3.3. **In these standards, it is referred to as "net outflows of secondary material" for "Module D"** (ISO 21930, EN 15804). It is a common practice in many market sectors including the building and construction market.

The system flow chart for a Net Scrap Substitution Approach is presented below in **Figure 5-1**. **The approach is based on a product life cycle and a comprehensive material stewardship perspective**. It not only incentivizes the use of recycled material for product manufacturing, but also takes into consideration the fate of products after their useful life and the resulting 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 evaluated. The specific nature of input material, e.g. primary or scrap, is important to calculate the cradle-to-gate footprint but is irrelevant to the calculation of the full life cycle footprint as typically **the net conservation of material is what minimizes the total environmental impacts**.

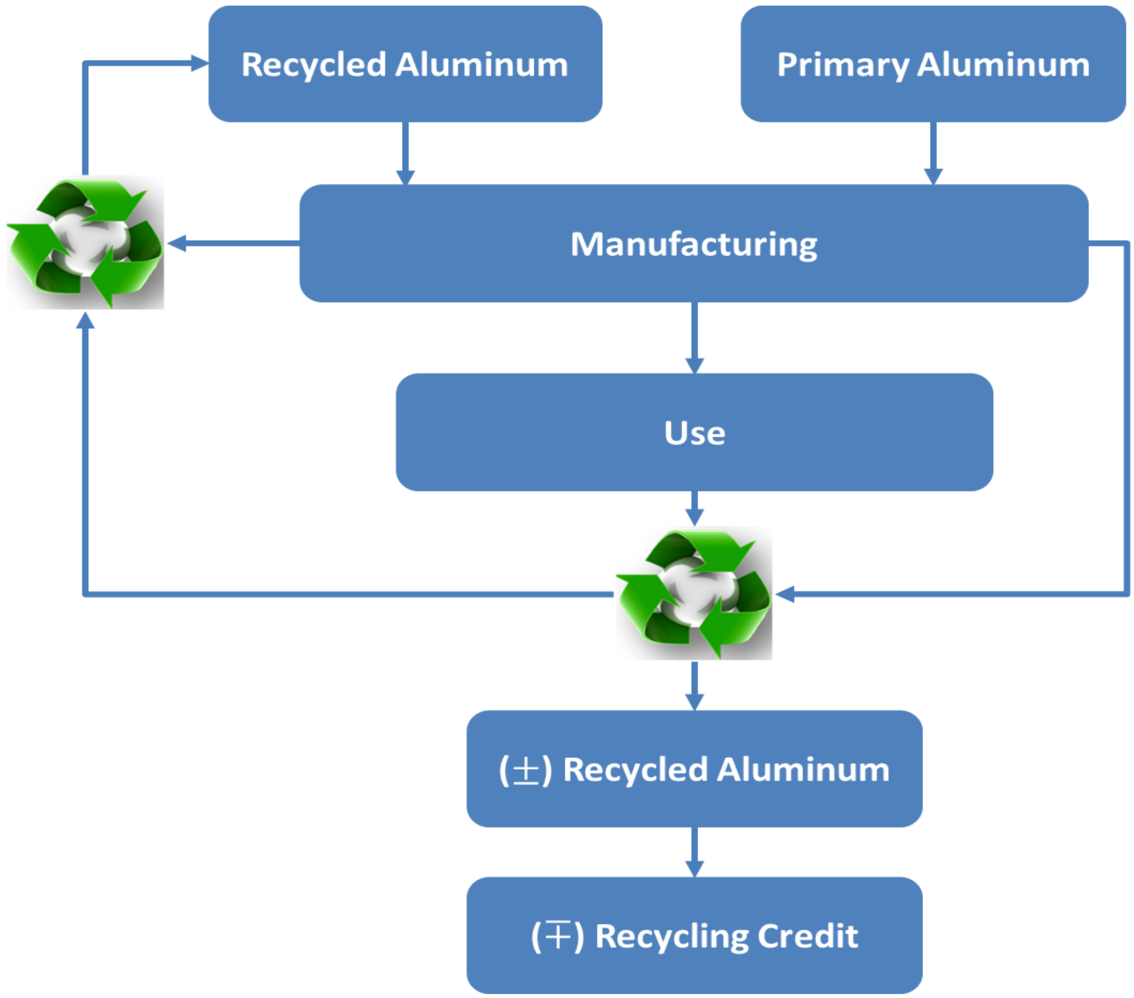

Figure 5-1: Process flow chart for the Net Scrap Substitution Approach

In practice, most semi-fabricated aluminum products are made from both primary and scrap/recycled metal. Scrap coming into the production system is assigned no embodied burden regardless of whether the scrap is pre-consumer or post-consumer.

In building the models, the demand of incoming scrap is first met by "looping back" scrap generated during the production processes and at the EOL recycling process (closed-loop). Such a treatment is the equivalent of replacing primary metal with scrap. At the end of life, it calculates the net amount of scrap sent to recycling and either "crediting" it, or "burdening" it, if the net scrap is negative. "Net scrap" is defined as the difference between the total amount of new and old scrap recovered during the production process and at the end of a product's service life, and the total scrap input for production. The generic formular for net scrap calculation is shown below:

$$
\begin{aligned}
Net\ Scrap = (&internal\ process\ scrap\ recovered\ for\ recycling \\
&+ preconsumer\ scrap\ recovered\ for\ recycling \\
&+ postconsumer\ scrap\ recovered\ for\ recycling) \\
&- (internal\ scrap\ input\ for\ production \\
&+ preconsumer\ scrap\ input\ for\ production \\
&+ postconsumer\ scrap\ input\ for\ production)
\end{aligned}
$$

If more scrap is recovered for recycling than is used as an input (**net scrap surplus,** shown in **Figure 5-1** as positive sign), a credit (shown in **Figure 5-1** as negative sign, meaning subtracting burden from the product system) is assigned to net scrap to reduce the life cycle footprint. If more scrap is required for manufacturing than collected for recycling (**net scrap deficit,** shown in **Figure 5-1** as negative sign), an embodied burden (shown in **Figure 5-1** as positive sign, meaning adding burden to the product system) is assigned to the net scrap to account for the loss of material. The embodied "burden" or "credit" is equal to the difference between the cradle-to-gate footprints of primary metal production and recycling:

$$\begin{aligned} &Credit\ or\ Burden \\ &= CradleToGate\ footprint\ of\ primary\ aluminum \\ &- CradleToGate\ footprint\ of\ aluminum\ recycling \end{aligned}$$

Methodologically, from a cradle-to-gate perspective, this calculation process is similar to the cut-off method. All upstream environmental burden of production is assigned to the product (product carries all burden – that's why no burden is assigned to scrap). ***On the other hand, from a cradle-to-grave perspective, it is similar to the substitution method***. Both double-counting and under-counting are prevented under this approach. From an environmental perspective, this allocation approach emphasizes both the use of recycled metal and the EOL metal recovery. By using more recycled material to make a product, the manufacturer is able to reduce the cradle-to-gate burden that the product system will carry along its life cycle stages, thus providing the same incentive to maximize the recycled content of one's product design as the cut-off approach. In addition, material recovery is rewarded at the end-of-life if more scrap is recovered than it is initially demanded. That same mechanism burdens the product system in case of a net scrap deficit, which is caused by material loss to landfill.

A designer using the Net Scrap Substitution Approach will focus not only on maximizing the use of recycled material, but also 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 promotes circular economy***.

The use of the Net Scrap Substitution Approach is based on the characteristics of aluminum products and aluminum recycling, which preserves the full physical properties of the metal with little quality loss no matter how many times it is recycled ***when recycled under optimal conditions***. The aluminum recycling system is a semi-closed-loop system in which recycled aluminum could end up with the same product system, e.g., extruded to extruded products, rolled to rolled products, and casted to 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 Net Scrap Substitution Approach also reflects the fundamental sustainability and environmental visions of the aluminum 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 5-2**).

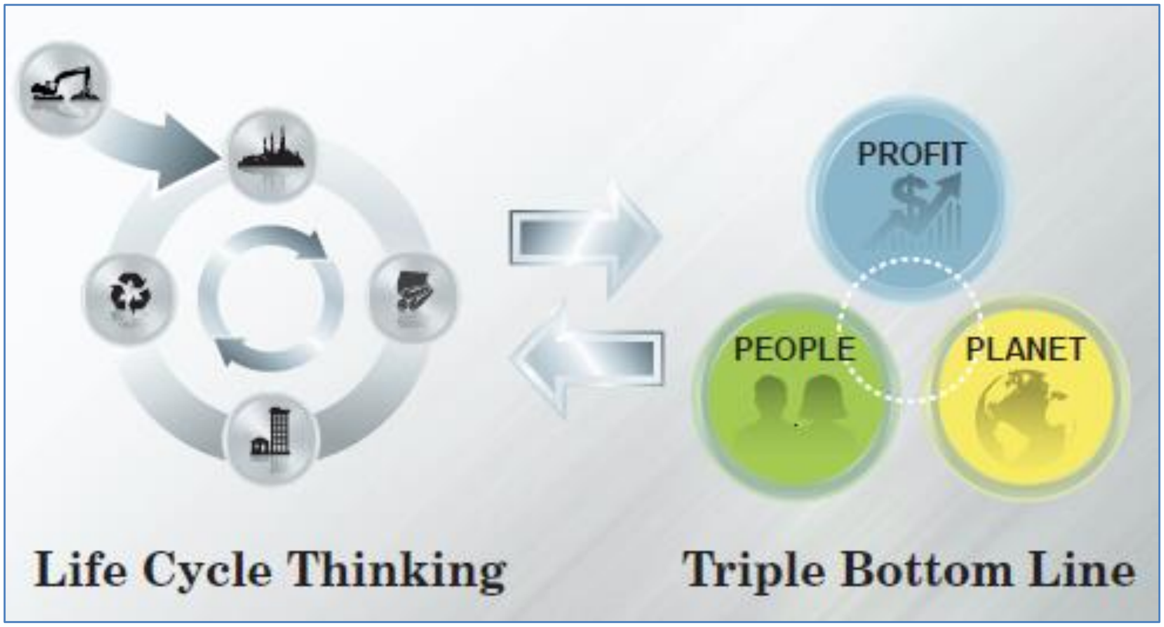

Figure 5-2: Sustainability vision of the aluminum industry in North America

On the other hand, the Aluminum Association also acknowledges that different methodological approaches exist in examining the environmental impacts of a product during its life cycle. For this reason, the Association takes a **transparent 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 more detailed information, industry average metal feedstock information at semi-fabrication mills is provided for each category of products in terms of primary metal, internal process scrap (run-around scrap), pre-consumer (new) scrap, and post-consumer (old) scrap. Assumptions are made to segregate scrap into appropriate categories whenever a data provider reported commingle scrap (mixture of old and new scraps) inputs.

What this report is unable to provide is the exact source of scrap generation particularly for new scrap, which would have been required in the case of a user adopting a method of assigning a specific embodied burden to scrap input based on its specific source of generation. This is due to the extreme complexity of scrap tracking along the value chain in the marketplace. Such complexity is not only reflected in the complex web of scrap generation, collection, storage, trade, and end-use along the value chain, but also potential commercial and legal consequences of sensitive information sharing.

5.2 Data Presentation

Data presented in this report is both detailed and comprehensive, adopting the highest possible level of transparency. The report contains necessary data and information for product and intermediate product systems in cumulative manner. In addition, **input and output information for unit production processes will be made available for users upon individual requests**.

Results of a wide range of sensitivity and scenario analysis are also presented to guide users and decision makers to appropriately adapt to their specific situation in which part of the parameters might differ from those reflected in the industry average models. **Such**

sensitivity and scenarios include changes in recycled content, EOL recycling rate, source of primary metal, among others. The scenario analysis and the presentation of its results are new to this report. It was not included in the previous report.

In the inventory analysis sections of the report, brief process descriptions, together with boundaries, assumptions, flow charts of the product model, and source of raw material and energy, are provided. Data quality assessments are included where possible. Cumulative LCI (on selected resources and emissions) is presented at each major sections for the examined intermediate and final product systems.

For life cycle impact assessment, it was determined during the scope development process that a comprehensive set of environmental impact categories were to be investigated. For the purposes of consistency with the past studies and the 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 (CO2) and other greenhouse gas (GHG) relevant emissions),
- Acidification Potential (AP),
- Eutrophication Potential (EP), and
- Smog Formation Potential (SFP)

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). An exception is the GWP, for which IPCC AR5 characterization factors were used. The TRACI is one of the most widely applied impact assessment methods in LCA studies around the world, particularly in North America.

Respective LCIA results are presented for the same product systems which LCI results are presented – in both "***cradle-to-gate***" and "***cradle-to-grave***" format. The presentation of these results will make it easy for users to directly utilize them to conduct their own analysis. For instance, if a user is particularly interested in the cradle-to-gate carbon footprint of automotive aluminum extrusion parts, a direct number is available. On the other hand, if a cradle-to-grave number factoring in EOL recycling is desired, a table is provided for users to calculate the values for each of the indicators corresponding to different EOL recycling rates.

6. Tracking the Source of Raw Materials

LCA is an environmental assessment that is based on models and assumptions. The results are often largely dependent on the quality of assumptions. Nevertheless, tracking the actual source of raw material supply can significantly improve the accuracy of the results. This is particularly true for corporate and plant level studies since corporations are supposed to have a clear record of where their raw materials are from. For industry level studies, it is still important to track the source of raw materials, at least at a macro level to reflect the most common patterns of material supply and flows, so that the results can be as representative to the truth as possible.

It is worth to mention that industry level source tracing is not carried out by following the supply chains of individual companies. For a study carried out by an association, such an action would not only be prohibited but also practically impossible given the large numbers of companies and manufacturing sites involved. Instead, the tracking is largely focused on analyzing industry statistics and international trade data to identify common patterns of material flows. Fortunately, the Aluminum Association has the luxury to do so with high level of accuracy since the Association has had a highly reputable statistical program that documents productions, shipments, end use, and international trades for the North American region – by market sectors and by product groups – for many decades.

6.1 Major Raw Materials

The product systems examined in this study include extrusion, sheet, foil, and die cast products. The manufacturing of these products takes place in two North American countries – Canada and the United States. The products are mostly shipped to downstream customers for additional forming, finishing and assembly before used by consumers. Major market sectors of product shipment include transportation, building and construction, durable goods, and packaging (in the case of foil). In addition, within the transportation market sector, automotive applications for extrusion and sheet products are separately presented in this study.

The manufacturing of these products usually starts from a cast house where raw material, which is solid metal, is remelted, purified, and alloy adjusted. It is subsequently casted into an ingot for hot and cold working (e.g., rolling or extrusion), or in the case of die cast products, is directly cast into a shape or component. Process diagrams for the productions of rolling ingot and extrusion billet are shown in **Figure 6-1** and **Figure 6-2**.

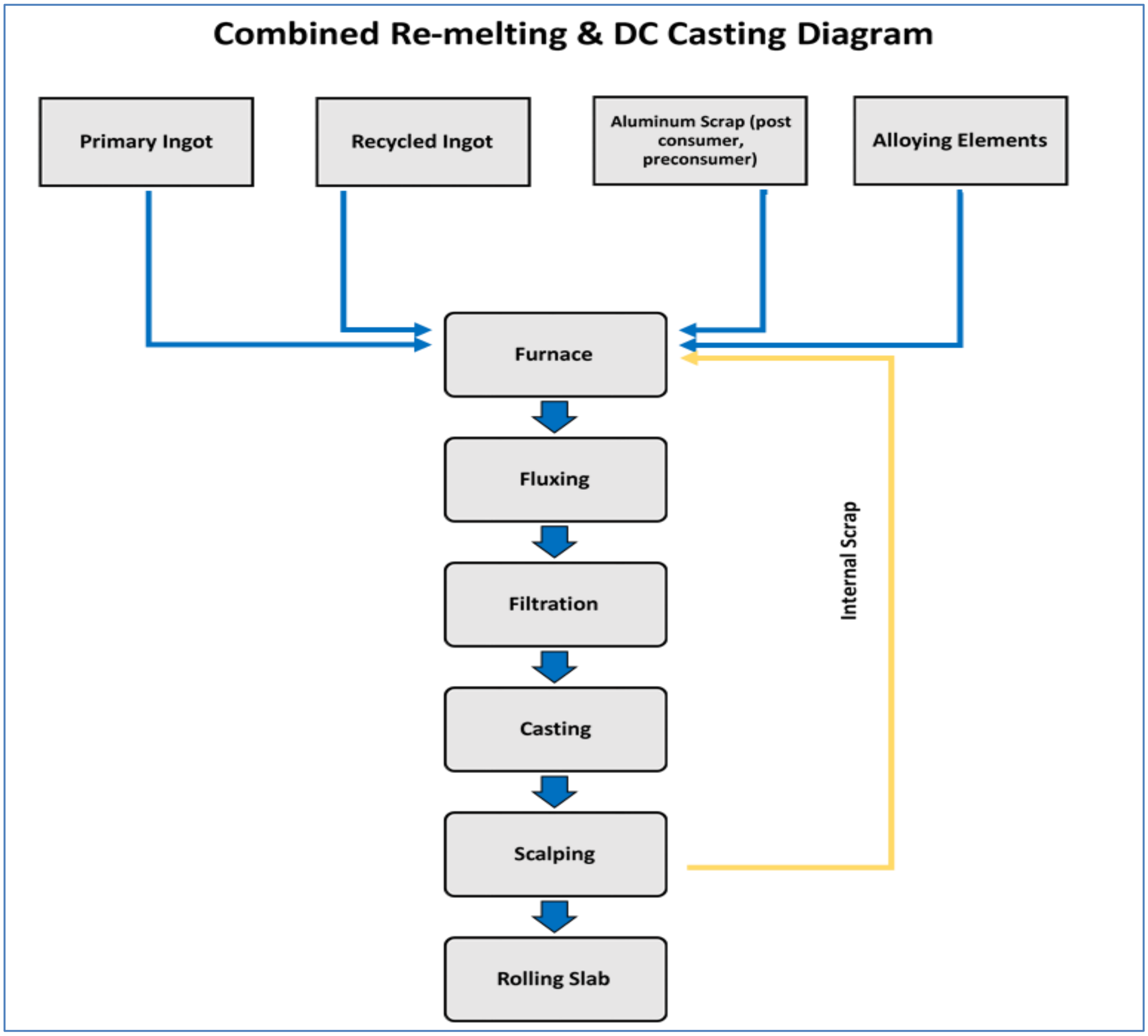

Figure 6-1: Illustration of rolling ingot production (DC casting)

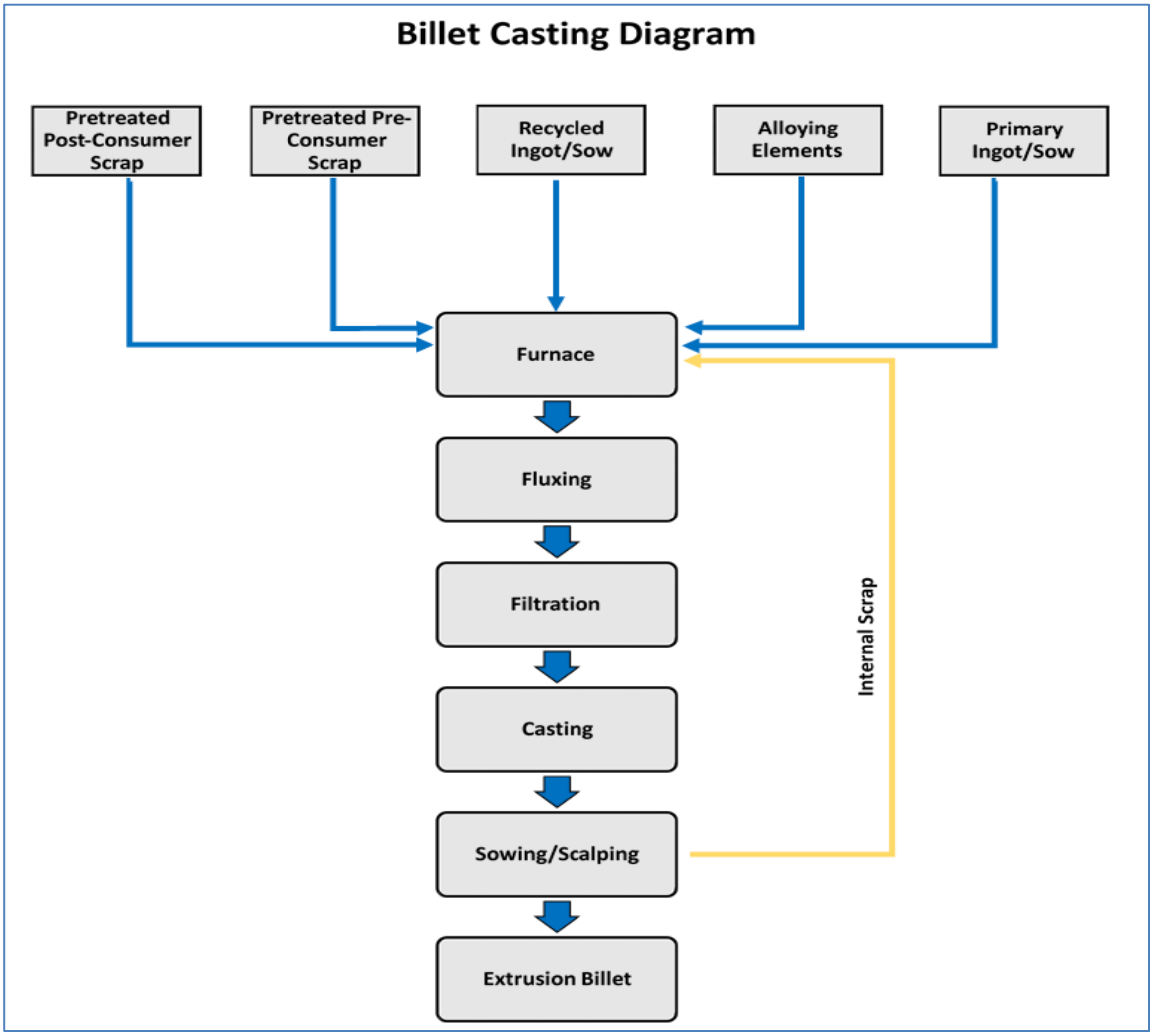

Figure 6-2: Illustration of extrusion billet production

Apparently, feedstock raw materials include primary metal, recycled metal, alloying agents, and scrap. Given the fact that recycled metal is also made of scrap and the quantity of alloying agents is very small, key raw materials for semi-fabrication can be narrowed down to only two categories: primary aluminum and aluminum scrap. Primary aluminum refers to non-alloyed aluminum ingot or molten aluminum produced directly from bauxite ore. It is also often called virgin aluminum. Aluminum scrap includes both pre-consumer (new) and post-consumer (old) scrap.

From a spatial perspective, sources of these raw materials vary. The purpose of source tracing is to identify the original geographic locations where the material is extracted or produced. The importance of such tracking is first related to transportation distances. Most importantly, it is connected to the types of electricity used for the production or extraction of these raw materials. In the case of aluminum scrap, it involves in tracking the generation and collection locations. In the case of primary aluminum, however, it involves not only in tracking the smelting sites but also the supply chain of smelters, from alumina all the way back to the cradle of aluminum – bauxite ore. The results of the raw material source tracking will serve as the framework for developing subset LCI models.

6.2 Aluminum Scrap

Aluminum scrap is a critical raw material for aluminum products, particularly in North America. Showing in **Figure 6-3** is the overall raw material supply in the North American market. Clearly, recycled aluminum/scrap is becoming the largest supply of raw materials in the region, followed by domestic produced primary aluminum, then imported ingots. It is worth to point out that the exact nature of imported ingots – whether it is primary or recycled metal – is unknown since international trade codes (Harmonized Tariff Schedule, HTS) do not differentiate primary and secondary aluminum ingot.

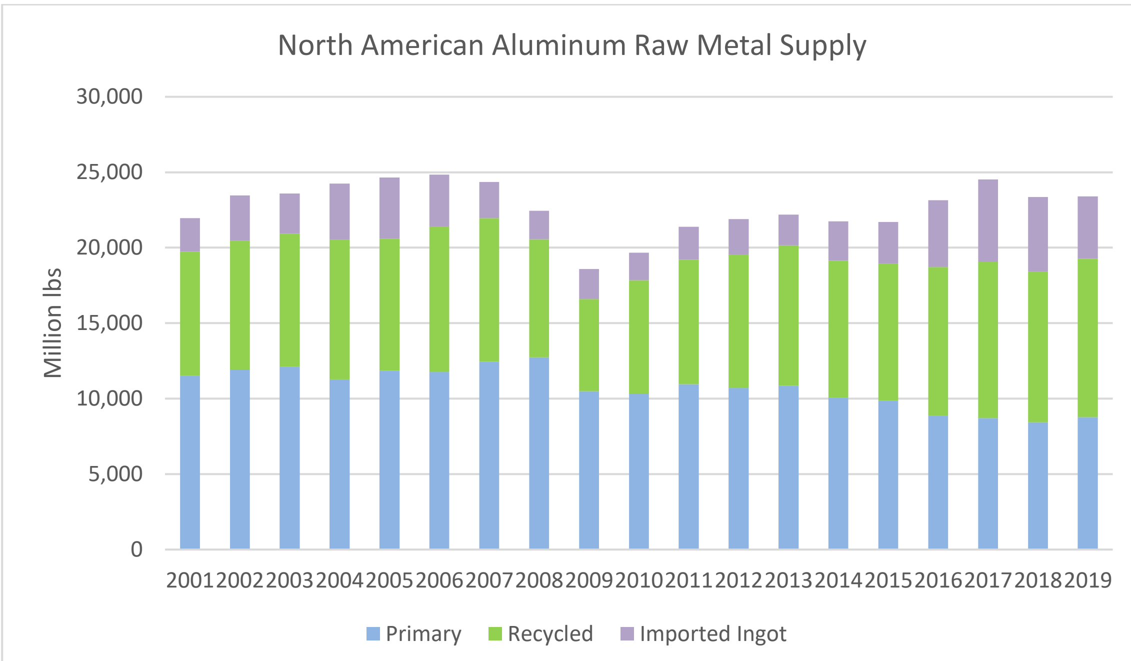

Figure 6-3: Aluminum raw metal supply (ingot or scrap) in North America market

From a trade perspective, North America is a net aluminum scrap exporter. Comparing to the amount of scrap imported each year, export on average is 5 times larger in the recent decade. This implies that scrap needed for domestic manufacturing is overall supplied by domestic source. **Figure 6-4** depicts the value chains of aluminum scrap and its flows. Overall, the vast majority of scrap is supplied by the U.S. and a minor fraction is supplied by Canada.

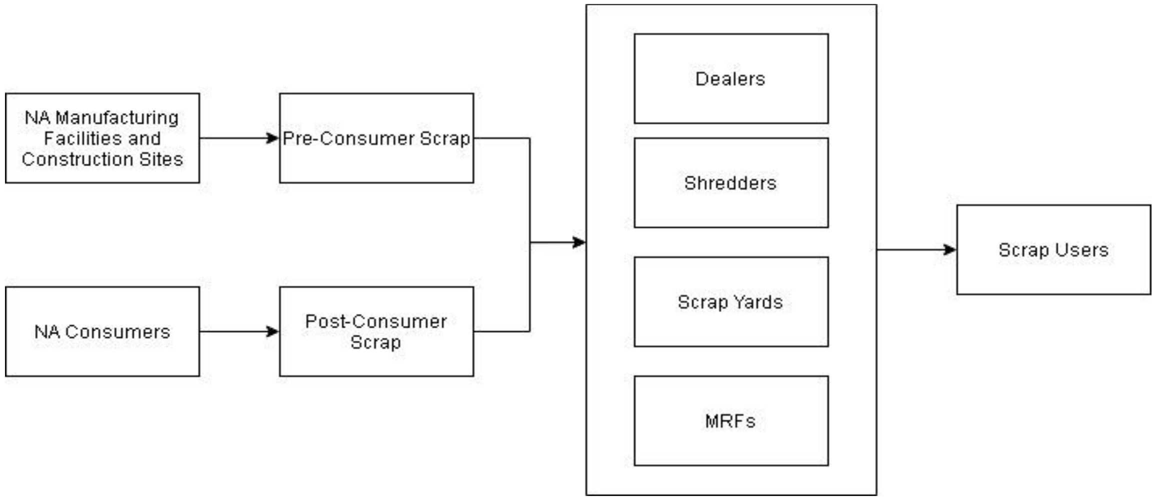

Figure 6-4: Aluminum scrap and supply chain tracking

New scrap is mostly generated by manufacturing facilities and construction project sites. One characteristic of new scrap is its generation is more concentrated than old scrap. The recycling of new scrap is a mature practice by the industry with a complex system of generation, collection, storage, trade and end use. No significant metal loss is expected in such a system. In some cases, manufacturers work together to form a closed-loop recycling system to ensure the scrap is well sorted, segregated, and recycled and reused in high quality and high value. This is reflected in the beverage can and automotive market sectors. In other cases, scrap flows from generators to third-party dealers and then end-up with users. In such cases, there is a possibility that scrap will get commingled with different alloys and lead to compromised quality of recycling.

Old scrap is mostly generated by consumers (including institutional and industrial consumers). An important characteristic for old scrap is its generation is highly dispersed and the timing of generation/availability is highly unpredictable. This leads to higher level of complexity for old scrap recycling.

Aluminum is a highly durable material. Historical aluminum applications in North America are largely in buildings, infrastructure, transportation equipment, and durable goods. These applications mean very long service life before the material is available for recycling. It also means that the source of recyclable material is likely in urban and dense population areas. During the past several decades, there has also been large quantities of aluminum applications for packaging, with aluminum beverage can being the main application. These products have a much shorter service life and get collected through the municipal solid waste management system. Aluminum recovered from beverage can recycling is mostly used to make new beverage cans again. Since aluminum can is not covered by this study, beverage can scrap will not be discussed here.

The collection of post-consumer aluminum scrap from buildings, infrastructure, transportation equipment, and durable goods is largely carried out by renovation and demolition contractors, used vehicle and equipment dealers, and scrap yards. Once the products containing aluminum – usually also containing other materials such as steel, copper, and plastics – are collected, they are further processed by the scrap yards themselves or by independent shredders. Through the dismantling and shredding processes, materials get sorted, segregated, sometimes cleaned, with aluminum sent to end users to be either made into mill products or recycled metal.

6.3 Primary Aluminum

Primary aluminum is another key raw material. In the North American market, the metal is traditionally supplied by Canada, U.S., Russia, the Middle East, and South America. Domestically produced primary aluminum (by Canada and U.S.) is almost all consumed within the region. Domestic production is concentrated in Canada, particularly in Quebec Province. In 2016, output from Canada was about 80 percent and output from the U.S. was about 20 percent. Overall, domestic production is about 81 percent of the total non-alloyed primary metal consumption. The rest of the demand is supplied by imports from Russia, the Middle East, South America, and the rest of the world (**Table 6-1**).

In is worth to point out that the consumption mix analysis is focused on non-alloyed primary aluminum, which is represented by the HTS code of 76011. In international trade codes, aluminum "ingot" – defined as unwrought aluminum for both non-alloyed and alloyed metal – is represented by HTS 7601. However, the four-digit code does not differentiate primary from secondary ingot, which uses mostly scrap as raw material. To avoid double counting by data users, this study only tracks net imports of non-alloyed aluminum ingots, which is unambiguously primary aluminum produced by electrolytic smelters using alumina as a feedstock material.

Table 6-1: Non-alloyed primary aluminum consumption mix in the North American market in 2016

Country/Region	Amount (Metric Tons)	Weight Factor for Model
NA Domestic	4,027,514	0.812
Russia	517,905	0.104
United Arab Emirates	176,252	0.036
Argentina	96,292	0.019
Brazil	14,460	0.003
Bahrain	14,983	0.003
Venezuela	36,810	0.007
Rest of World	75,542	0.015
Total	4,959,757	1.000

Source: The Aluminum Association (NA domestic production); GTIS.COM (U.S. non-alloyed aluminum ingot imports, subscription required); Bureau of Census, U.S. Department of Commerce (U.S. aluminum imports and exports); Statistics Canada (Canadian aluminum imports and exports).

With these source regions and countries of primary aluminum supply, the next step is to track further back in the supply chain – to the cradle. Major raw materials in the supply chain include alumina and bauxite ore. The ideal situation for a more accurate LCI model is to be able to track sources of supplies of these materials for each of the primary metal production regions/countries involved. Unfortunately, other than North America itself, statistical data for other countries is not available. Therefore, the models of this study have been concentrated on reflecting the actual supply chain of NA domestic smelters. At the same time, it relied on IAI primary aluminum production models for other countries and regions in which the rest of metals are imported from. **Table 6-2** is a summary of raw material sources for primary aluminum production that was reflected in the subset models of this LCA. Details will be illustrated in the inventory analysis in the next chapter.

Table 6-2: Primary aluminum production regions and their supply chain tracking

Primary Aluminum Production Region	LCI Subset Models for Primary Metal	Source of Alumina	Source of Bauxite
NA Domestic	AA/Sphera	• Domestic • Australia • Suriname • Brazil • Jamaica	• Jamaica • Brazil • Guinea • Guyana • Others
Russia	IAI – Russia & Other Europe	• Europe	• South America
• **U. A. E.** • **Bahrain**	IAI – Middle East	• Australia	• Australia
• **Argentina** • **Brazil** • **Venezuela**	IAI – South America	• South America	• South America
Rest of World	IAI – Global	• Global	• Global

7. Life Cycle Inventory Analysis

7.1 Primary Aluminum

The life cycle stages of primary aluminum production includes the component processes of bauxite mining, alumina refining, electrolysis (including anode production and smelting), and primary ingot casting. A LCI model for the production processes is shown in **Figure 7-1**. 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.

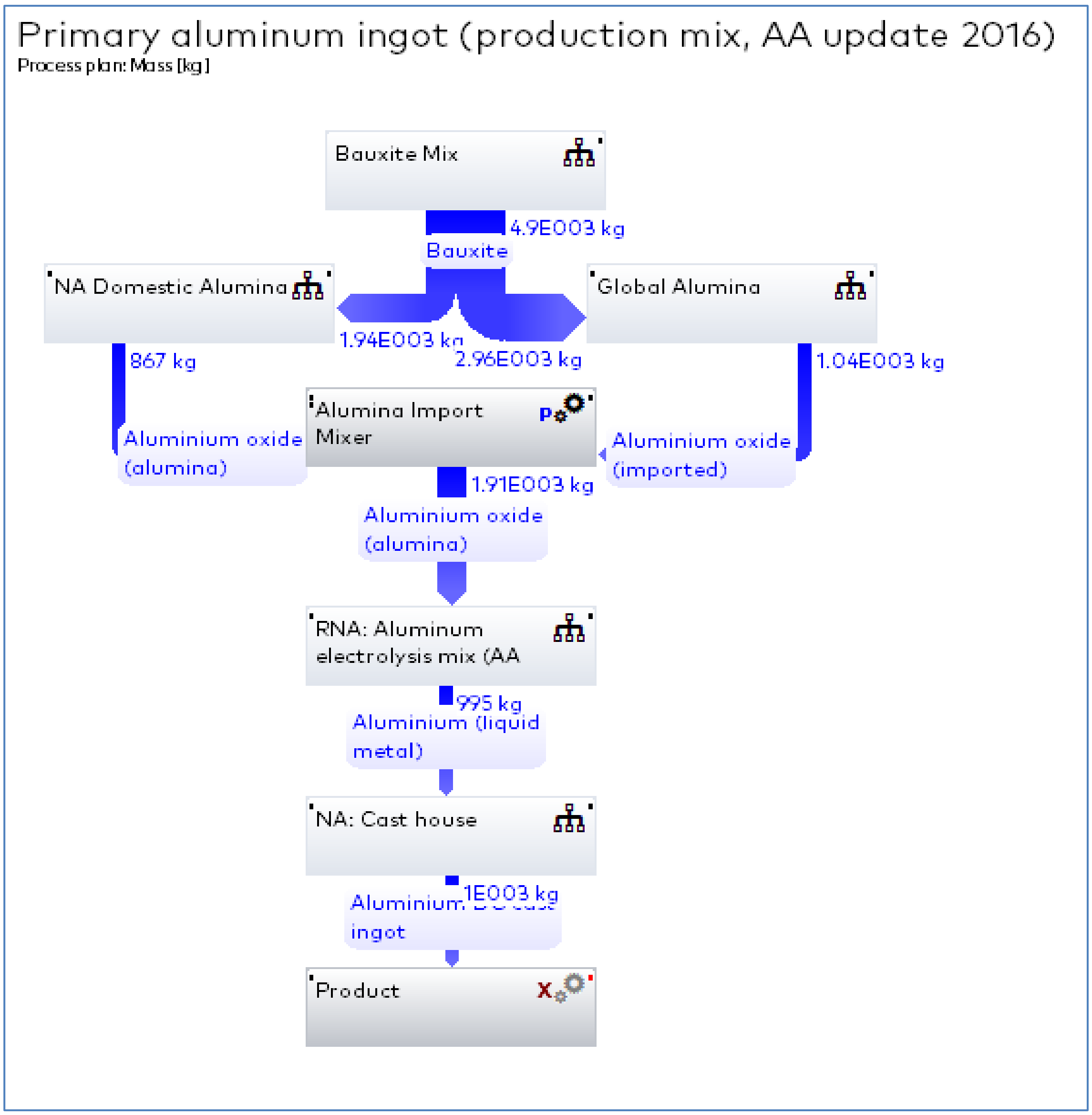

Figure 7-1: Domestic primary aluminum production model, for 1,000 kg of primary aluminum ingot

As it is explained in **Chapter 6**, primary aluminum production is done both domestically in North America and in countries where it is imported from. The model is based upon survey data obtained from IAI. Source of major raw materials in each of the unit processes is based upon statistical data of production, shipment and international trade published annually by the Aluminum Association, the U.S. Geological Survey (USGS), and the United Nations Comtrade Database (UN Comtrade). Source of energy, particularly electric power in the smelting and ingot casting processes, is based on power contracts and on-site power generation (captive power) 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 survey data was directly collected from bauxite mining, alumina refining, and primary aluminum smelting facilities around the world. The subset for North America is a result of aggregated reporting from North American facilities. The subset for net imports is an aggregation of results generated by IAI regional and countries level models. Therefore, the nature of this LCI dataset is the primary data in aggregated format. Overall, the quality and consistency of the IAI data have been identified as of high quality.

7.1.1 Production Processes

7.1.1.1 Bauxite Mining

7.1.1.1.1 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 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; AA, 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.

7.1.1.1.2 Source of Raw Material and Energy

Nearly all bauxite consumed in North America was imported. Domestic bauxite mining is negligible and most of it is utilized for non-metallurgical applications such as abrasives, chemical, refractory materials (USGS, 2017). Total metallurgical (i.e. to produce metallic aluminum) bauxite imports and the country of origin in 2016 are given in **Table 7-1** and **Table 7-2**.

Table 7-1: 2016 North America bauxite imports for domestic alumina production (in metric tons)

Country/Region	Quantity
USA	6,201,000
Canada	3,581,000
NA Total	9,782,000

Data source: USGS, 2017; UN Comtrade, 2017.

Table 7-2: Major source of bauxite imports to North America in 2016 [USGS, 2017] by country

Country	Share of bauxite imports
Jamaica	42.0%
Brazil	26.0%
Guinea	23.0%
Guyana	5.0%
Others	4.0%

Note: It is assumed that Canada has the same source of importing as the US (data for Canada is not available).

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

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

7.1.1.2 Alumina Production

7.1.1.2.1 Unit Process Description

Alumina is the major feedstock for primary aluminum production. The North American industry sources its majority of alumina from other countries. Approximately 46 percent of alumina is domestically produced and 54 percent is imported from other countries. According to USGS, major countries of alumina imports by the United States in 2016 include Australia, Suriname, Brazil and Jamaica.

Alumina refining is a process of converting bauxite to aluminum oxide Al_2O_3 (alumina) using the Bayer process. 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 (caustic soda) 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 residues 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; AA2013):

- 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.

7.1.1.2.2 Source of Raw Material and Energy

Raw materials for alumina production include bauxite, caustic soda, sodium carbonate, etc. As it is mentioned in **Section 7.1.1.1.2**, all bauxite is imported and the countries of origins 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.

7.1.1.3 Anode Production

7.1.1.3.1 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 (Na_3AlF_6) 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 CO_2 gases (Altenpohl, 1998).

There are two generic types of reduction cells: prebake and Söderberg (Anseen et al, 1979; Bergsdal et al, 2004; AA, 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, the Söderberg technology has been phased out. All facilities are now using prebake technology.

The operations associated with anode production include (AA, 1998; AA, 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 transported to a primary aluminum smelter.

7.1.1.3.2 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 sourced from local providers, so does energy for the productions. Due to the minimal effect on the overall footprint by variations in the source of raw material and energy, a global average profile is used to represent both domestic productions and imports of anodes consumed in North America.

7.1.1.4 Aluminum Smelting – Electrolysis

7.1.1.4.1 Unit Process Description

Molten aluminum is produced from alumina by the Hall-Heroult electrolytic process (Grjotheim et al, 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. Söderberg technology has been phased out in North America. Prebake is the predominant technology. As a consequence of advanced design and better computer control of the Prebake technology, the efficiency and emission levels have been significantly improved.

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 wastewater 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; AA, 2013):

- preparation, recovery, 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.

7.1.1.4.2 Source of Raw Material

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

As described in the previous unit process, about 46 percent of alumina consumed in North America in 2016 was produced domestically and the rest of it was imported. Carbon anodes were also partly domestic produced and partly imported. Other auxiliary materials were either imported or domestically produced but the quantities of consumption of those materials were minor.

7.1.1.4.3 Source of Energy – The Electrical Power Mix of Domestic Production

Electricity is the primary energy source of the electrolysis process. Electricity serves in this case both as energy and as "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. 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 actual source of power generation and the corresponding quantities of consumptions at the production facilities covered by this study.

Unlike most other manufacturing industries in which electricity usually comes from a general grid with a mixture of power generation sources, primary aluminum smelting companies in North America get their electricity either through special power purchasing agreement with specific utility companies or through building and operating their own generation facilities (captive power). Aluminum smelters are often located close to a power generator. In the case of power purchase, the smelters are categorized as **base load**

consumers due to the stable amount of consumption all time around. Consequently, the aluminum industry is unique in its ability to identify the specific source of power generation, e.g., its exact energy footprint. 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 2016 production year power mix is shown in **Table 7-3**:

Table 7-3 : Electrical power mix of North American primary aluminum production in 2016

Power Source	Power Consumption (GWh)	Share of Power Source	Composition of Power Intensity (kWh/1000 kg Al)
Hydro	45,534	78.4%	12.24
Other Renewable	938	1.6%	0.25
Nuclear	233	0.4%	0.06
Coal	9,791	16.9%	2.63
Natural Gas	1,564	2.7%	0.42
Oil and Other	36	0.0%	0.01
Total	58,096	100.0%	15.61

Source: IAI 2016 Energy Survey.

7.1.1.4.4 North American Primary Aluminum Consumption Mix

As it is illustrated in **Section 6.3**, domestic production is the majority of primary aluminum supply. Accompanying with closures of old smelters in North America during the past decade, an increasing share of primary metal has been imported. This needs to be reflected in the LCA models so that the environmental footprint of aluminum products can be more accurately documented.

The consumption mix is a reflection of primary metal supply for the North American semi-fabrication industry on a weighted average basis (**Table 6-1**). Subset LCI models are developed to reflect each of the production regions and countries and the life cycle inventory of the consumption mix is calculated by summing up all the relevant regions and countries. These include NA domestic production, Russia, United Arab Emirates, Bahrain, Brazil, Argentina, Venezuela, and the rest of world.

7.1.1.4.5 Perfluorocarbon (PFC) Emissions in Aluminum Smelting

PFC emissions (as Hexafluoroethane and Tetrafluoromethane gases) in the aluminum smelting process are listed in **Table 7-4**.

The CO_2 equivalents (100 years) of the emissions are calculated based on IPCC Fifth Assessment Report[1] values of 66,30 (kg) for CF_4 and 11,100 (kg) for C_2F_6.

Table 7-4: Perfluorocarbon (PFC) emissions of aluminum smelting in North America in 2016, representing 1000 kg of aluminum ingot

Category	Unit	Amount
Tetrafluoromethane (CF_4) (CO_2 eq./ton aluminum ingot)	kg	234.7
Hexafluoroethane (C_2F_6) (CO_2 eq./ton aluminum ingot)	kg	36.6

Source: Based on input and output data for the electrolysis process of NA domestic production

7.1.1.5 Primary Ingot Casting

7.1.1.5.1 Unit Process Description

Molten metal siphoned from the pots is sent to a resident cast house found in each smelter. It is then transferred to a holding furnace where alloy elements may be added to make a specific alloy requested by a customer. In the case of non-alloyed ingot, no alloy elements are added.

When 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. Dross contains small quantities of trapped aluminum metal and therefore is further processed, usually by special aluminum recycling companies, to recover the aluminum content.

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 non-alloyed ingot), direct chill molds, or electromagnetic molds.

This unit process begins with the processing of molten primary aluminum and ends with the output of ingots, either unalloyed or alloyed. The various operations carried out in the cast house include (AA, 1998; AA, 2013):

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

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

7.1.1.5.2 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 a smelter so the source of energy is the same as the electrolysis process.

Alloying elements may be added during ingot casting. However, as stated in **Section 4.3.6**, these materials will be substituted by the same amount of aluminum elements in the LCA model for simplicity and other considerations.

7.1.2 LCI Results of Primary Aluminum Ingots

In this section, the LCI of primary aluminum are presented for 1 metric ton of aluminum ingot, in the format of both **domestic production mix** and **consumption mix** for North America. The consumption mix includes net imports of unalloyed metal from other countries.

The models used to calculate the LCI are shown in **Figure 7-1** and **Figure 7-2**. The results of the LCI are shown in **Table 7-5**. The breakdown of inventories for energy and carbon dioxide emissions is shown in **Table 7-6** and **Table 7-7**. Analysis of the two highlighted inventory items is shown in the subsections followed.

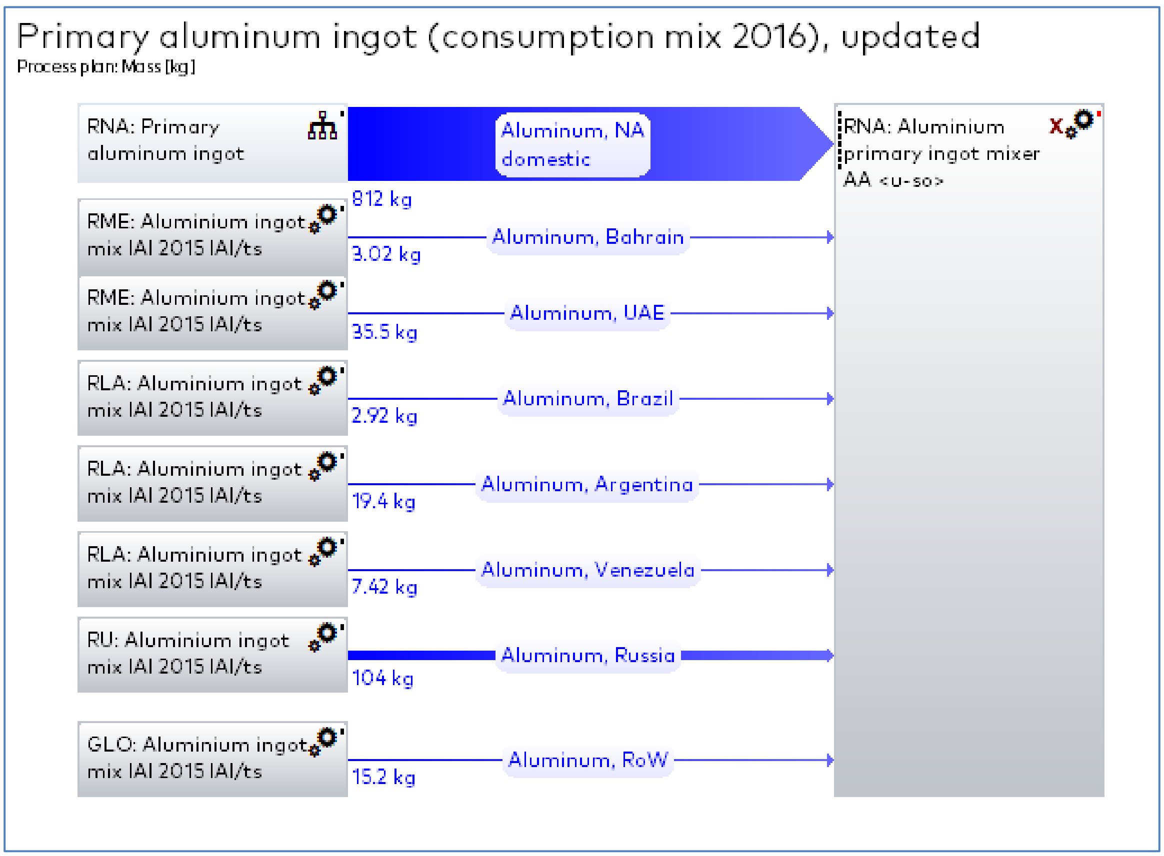

Figure 7-2: North American primary aluminum consumption mix model for 1000 kg of primary aluminum

Table 7-5: Selected LCI for 1,000 kg of primary aluminum ingot in North America

Inventory Category	Primary ingot (domestic production)	Primary ingot (consumption mix in market)
Energy (MJ)		
Non-renewable energy	8.15E+04	8.28E+04
Hydroelectric energy	5.27E+04	5.18E+04
Other renewable energy (non-hydro)	1.15E+03	1.08E+03
Resources (kg)		
Bauxite	5.42E+03	5.44E+03
Net fresh water (excluding energy)	1.12E+04	7.60E+03
Air Emissions (kg)		
Carbon dioxide	7.87E+03	7.84E+03
Carbon monoxide	2.05E+00	2.51E+00
Chlorine	1.53E-04	2.20E-04
Fluorine/Fluorides	3.69E-01	3.62E-01
Hydrogen chloride	1.15E-01	1.20E-01
Hydrogen fluoride	3.43E-01	3.67E-01
Nitrogen oxides	1.09E+01	1.29E+01
Nitrous oxide	9.53E-02	9.06E-02
Sulphur oxides	1.62E-15	1.31E-15
Non-methane VOCs	7.83E-01	9.86E-01
Methane	9.72E+00	1.03E+01
Dust (PM10)	7.11E-03	6.67E-01
Dust (PM2.5)	1.95E+00	2.00E+00
Fresh water Emissions (kg)		
Biological oxygen demand (BOD)	1.35E-02	1.43E-02
Chemical oxygen demand (COD)	3.56E+00	3.18E+00
Heavy metals	5.15E+01	4.19E+01
Ammonia	1.06E-03	9.95E-04
Fluorine/Fluorides	1.87E+00	1.65E+00
Phosphate	4.54E-03	4.24E-03
Solid waste (kg)		
Total waste (excluding mining overburden)	3.85E+03	3.95E+03

Table 7-6: Primary energy and CO_2 emissions breakdown by unit process for the production of 1000 kg of primary aluminum ingot in North America

Primary aluminum ingot (domestic)						
Inventory parameter	**Unit**	**Bauxite mining**	**Alumina refining**	**Electrolysis**	**Cast house**	**Total**
Primary energy demand	GJ	0.61	32.87	99.93	1.91	135.32
Non-renewable	GJ	0.59	31.48	47.57	1.83	81.48
Renewable	GJ	0.02	1.39	52.35	0.08	53.84
CO2 emissions	MT CO2	0.05	2.65	5.07	0.11	7.87

Note: CO2 emissions represent one of the greenhouse gases. Total GHG emission results are shown in the LCIA results.

Table 7-7: Primary energy and CO_2 emissions breakdown by countries and regions for the consumption mix of 1000 kg of primary aluminum ingot in North America

Inventory parameter	**Primary energy demand (GJ)**			**CO2 emissions (MT CO2)**
	Subtotal	**Non-renewable**	**Renewable**	
North America	109.88	66.16	43.72	6.39
Russia	12.81	5.33	7.48	0.52
United Arab Emirates	5.62	5.57	0.05	0.40
Argentina	2.71	1.84	0.87	0.18
Venezuela	1.04	0.70	0.33	0.07
Bahrain	0.48	0.47	0.00	0.03
Brazil	0.41	0.28	0.13	0.03
Rest of World	2.75	2.46	0.28	0.23
Total	135.69	82.82	52.86	7.85

Note: CO2 emissions represent one of the greenhouse gases. Total GHG emission results are shown in the LCIA results.

7.1.2.1 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.

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:

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

It is essential for non-LCA practitioners and non-technical professionals to understand the fundamental difference between the term **energy consumption** for daily life circumstances 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. In addition, energy demand related to all kinds of transportation is included as well.

The breakdowns of PED **by unit processes** and **by production countries** are illustrated in **Figure 7-3** and **Figure 7-4**, respectively, including non-renewable and renewable resources. The production of 1 metric ton of primary aluminum ingot, representative for both the production mix and consumption mix, requires 81.5 GJ and 82.8 GJ of energy from non-renewable sources, and 53.8 GJ and 52.9 GJ from renewable sources, respectively. The electrolysis process accounts for approximately **74 percent** of the total PED (with anode production contributes approximately 14 percent of the PED for electrolysis). It is a 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 **approximately 80 percent of the electricity is from hydropower and other renewable energy generation**. However, as a result of the different power generation efficiencies and the higher fraction of non-renewable energy demand for other production processes, the overall non-renewable fraction of primary energy demand for primary aluminum is still greater than the renewable fraction. Renewable energy is **40 percent** of the total energy demand and non-renewable energy is **60 percent**.

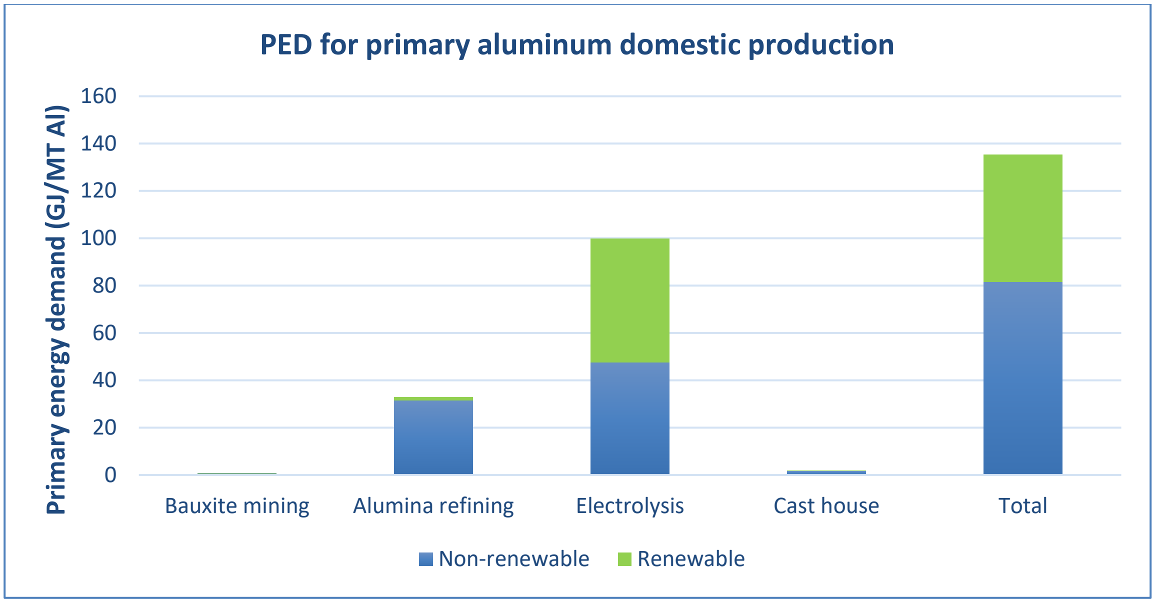

Figure 7-3: Primary energy demand from renewable and non-renewable sources for primary aluminum domestic production, by unit process and in total.

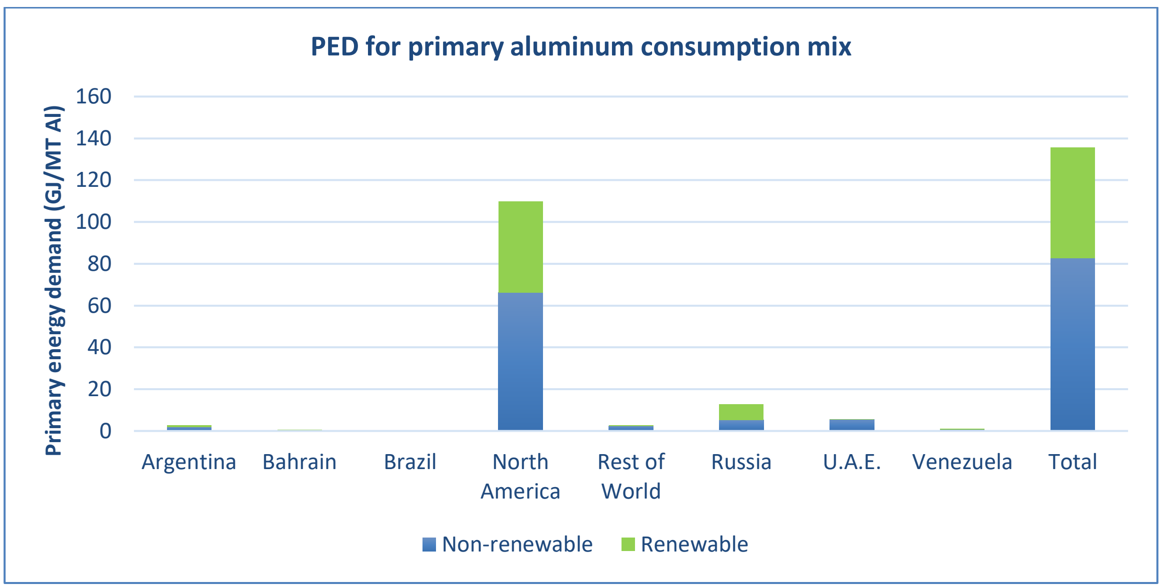

Figure 7-4: Primary energy demand from renewable and non-renewable sources for primary aluminum consumption mix, by regions and countries and in total.

7.1.2.2 Carbon Dioxide Emissions

Carbon dioxide is one of the greenhouse gases that contributes to the global warming phenomenon. Other gaseous emissions that cause global warming phenomenon from primary aluminum production processes include methane (CH4) and perfluorocarbon (PFC). **In this section of inventory analysis, the focus is on carbon dioxide**.

Carbon dioxide emissions are mainly associated with the conversion of fossil energy carriers (e.g. coal, 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 7-5** and **Figure 7-6** for both **domestic production** and

consumption mix, respectively. It is calculated that 7.87 metric tons of carbon dioxide is associated with per metric ton of domestic primary aluminum ingot produced. From a consumption mix perspective, that number is 7.85, with domestic production contributing 81 percent.

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 5.07 metric tons – or **64 percent** – of carbon dioxide for each ton of domestic primary aluminum ingot produced. **The upstream emissions associated with the electricity supply chain account for 70 percent, or 3.55 metric tons of CO_2 emissions, of the electrolysis process itself**.

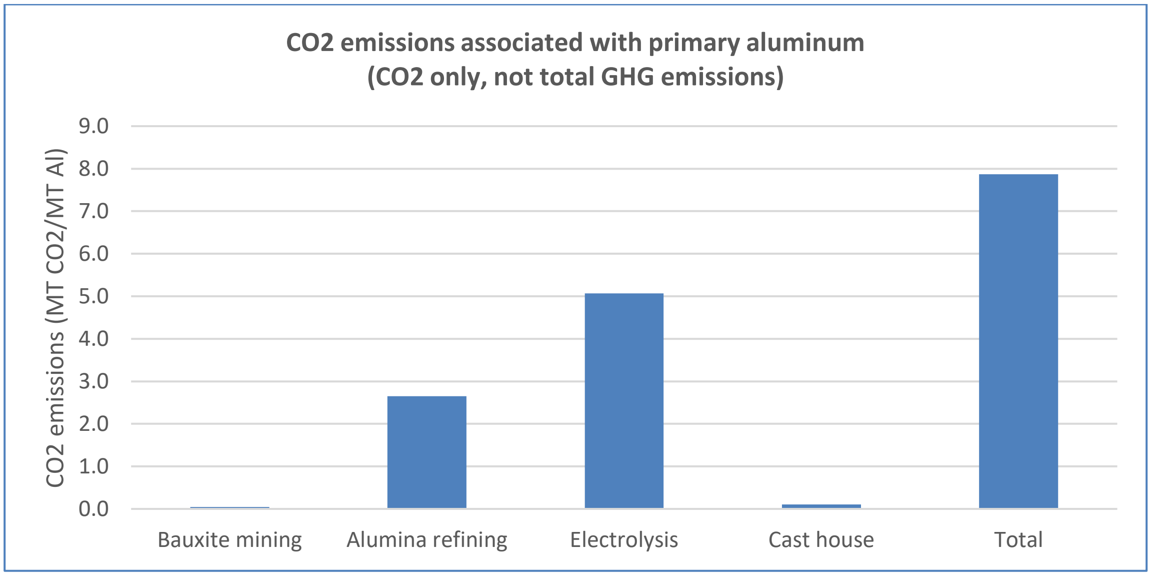

Figure 7-5: Carbon dioxide emissions associated with primary aluminum domestic production, by unit process and in total.

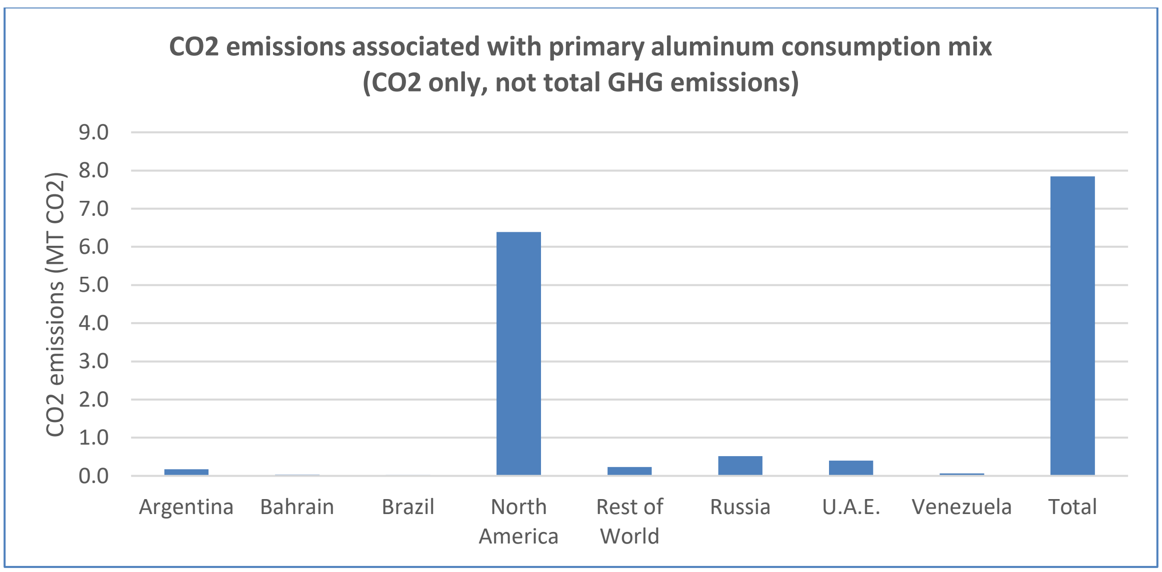

Figure 7-6: Carbon dioxide emissions associated with primary aluminum consumption mix, by regions and countries and in total.

7.2 Aluminum Recycling (Secondary Production)

Aluminum recycling, or secondary metal production, uses aluminum scrap as major feedstock. After scrap is "mined" – collected – it is sorted and cleaned before it is used in metal production. The raw material can be categorized into "new" and "old" scrap.

New scrap, often called pre-consumer or post-industrial scrap, is generated from both 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. Other names for old scrap include postconsumer, end-of-life and obsolete scrap. Common sources for old scrap include automobile parts, beverage cans, demolition scrap from building and infrastructure, and components and parts from durable goods.

A quantitatively less important but symbolically significant source of recycled aluminum feedstock 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 extracting metal from dross and concentrated salt cake. This is a new movement reflecting the industry's commitment in improving production efficiency and reducing wastes.

Production models are shown in **Figure 7-7** and **Figure 7-8**. The models are based on ***direct survey data*** collected through data survey by the Aluminum Association. Therefore, the nature of this LCI dataset is the primary data in aggregated format. Data coverage is shown previously in **Section 4.1.4**. Overall, the data quality is considered high.

Attention must be paid to the difference of the two models, in which one model (**Figure 7-7**) involves melting of 100 percent scrap without any addition of primary aluminum and alloy elements, while the other model (**Figure 7-8**) involves adding about 5 percent of primary aluminum and alloy elements to adjust alloy composition for specific end uses. The model with 100 percent scrap input is developed to represent **a pure aluminum recycling process**. The end-product is recycled ingot. Meanwhile, the model that involves in adding primary aluminum and adjusting alloy composition is developed to represent **the production of remelt secondary ingot (RSI)**, a common term widely used by the secondary aluminum producers.

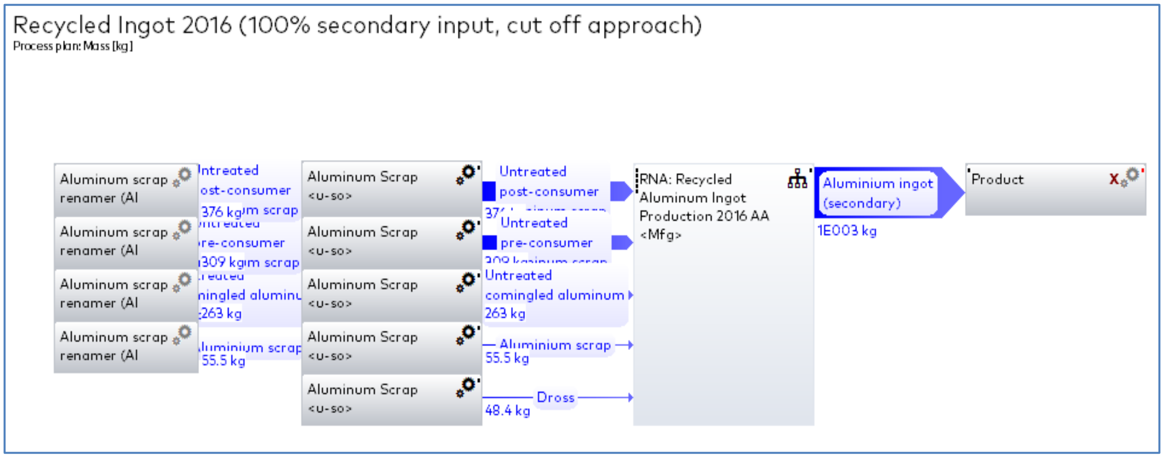

Figure 7-7: Illustration of the aluminum recycling model, representing 1000 kg of recycled aluminum ingot

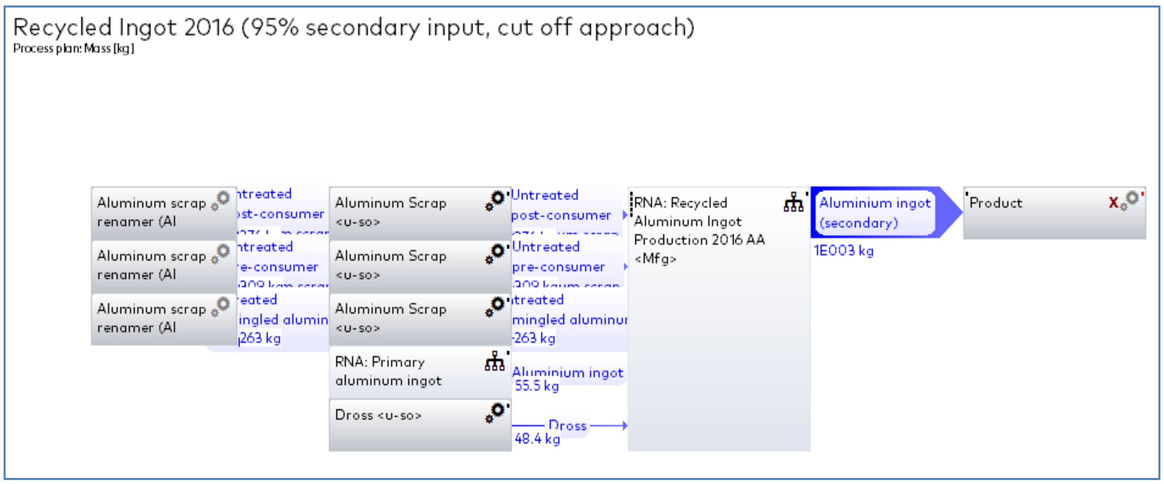

Figure 7-8: Illustration of the recycled specification ingot production model, representing 1000 kg of RSI ingot

7.2.1 Production Processes

The core of recycled aluminum production is the melting & casting process. Pre-treated scrap is fed into melting furnaces to liquefy the metal. It is then purified, adjusted to designated alloy, and cast into a form suitable for subsequent processing and fabrication. The process starts with the collection and treatment of scrap.

7.2.1.1 Scrap Treatment

7.2.1.1.1 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 with the case with bauxite. The “deposits” are “retired” individual pieces of metal that are either attached to an object, a facility, or loosely scattered around. New scrap is relatively concentrated comparing to old scrap. But such concentration can not match with the level of bauxite mines.

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. This study does not include scrap collection in the production models since no such data can be obtained from stakeholders.

After it is collected, scrap is sorted, cleaned and pre-treated. 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 pretreatment steps include shredding and crushing, drying and sweating, and de-coating or de-lacquering. Scrap treatment helps reduce aluminum loss within the melting furnace and lowers emissions 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 of raw material and auxiliary material;
- Scrap sorting including hand, mechanical and robotic sorting;
- 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, 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-treated "clean" aluminum scrap, transported or transmitted to melting furnaces.

7.2.1.1.2 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 more than one million metric tons 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.

7.2.1.1 Scrap Melting & Ingot Casting

7.2.1.1.1 Unit Process Description

Aluminum scrap melting is the process of feeding treated 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 if necessary, and casting it into desired shapes for subsequent use. In many cases, the product will be used as a feedstock material to make wrought or cast products. This means that the ingot will go through another remelting process before it is used for semi-fabrication. **Many vertically integrated semi-fabrication facilities also act as recyclers for which they directly use scrap to make semi-fabricated products. That will be elaborated in the next semi-fabrication section of the report**.

7.2.1.1.1.1 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.

In North America, reverberatory and rotary furnaces are the most common types of furnaces used to melt many different grades of aluminum scrap. These types of furnaces are usually natural gas fired and 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" molten aluminum during the aluminum scrap melting process in which the feedstock is partially oxidized or highly impure. Salt is a mixture of sodium and potassium chloride (NaCl and KCl) with several percent of cryolite (Na_3AlF_6) added. 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. Gas fluxing is the most used method. It involves the injection of gases such as chlorine, nitrogen, or argon below the surface so that the gases can stir the molten metal, react with contaminants and/or raise them to the surface for skimming.

7.2.1.1.1.2 Alloy Adjustment

Once contaminants are removed, the metal may require the addition of other elements to meet the final product specification. Aluminum scrap usually contains a variety of alloy elements by itself. Alloy adjustment is the process by which the chemistry of the metal is modified through the addition of such elements. Primary aluminum may be added to dilute certain elements that exceed customer's specified limits. Copper, magnesium, manganese, 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.

7.2.1.1.1.3 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. There are several routes for further processing of the resulting metal. Any particular route will be depended on product and customer specifications.

7.2.1.1.1.4 Emissions

Dust generation and air emissions are typical at both scrap processing and melting facilities. Chloride gases, and volatile organic compounds (VOCs) 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.

7.2.1.1.1.5 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:

- 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 recycled aluminum ingots transported to an end use facility.

7.2.1.1.2 Source of Raw Material and Energy

The source of major raw material for this unit process is the pre-treated aluminum scrap – the output of the previous unit process. Most facilities process untreated 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 source of energy. Electric furnaces use electric power as the major energy source. Unlike primary aluminum producers, most secondary producers in North America do not purchase electricity from specific power generators, nor do they own any power generation facility. In stead, they purchase their power from local utility companies.

7.2.1.2 Dross and Salt cake Recycling

7.2.1.2.1 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 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 three 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 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 are subsequently charged into remelting 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;
- Remelting the pre-processed metallic dross and dross concentrates, and refining and purification of molten metal;
- Batching and casting operations;
- Sawing, and packaging;
- Extraction of salt from residues;
- 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 customer.

7.2.1.2.2 Source of Raw Materials and Energy

The source of raw materials for this unit process is the production waste from aluminum scrap melting facilities and cast houses including cast houses of primary aluminum producers. In all cases, the raw materials are all from North America, usually from the nearest secondary or primary producers. The source of auxiliary materials is mostly domestic and/or local.

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

7.2.2 LCI of Aluminum Recycling and Recycled Specification Ingot

This section presents LCI results of aluminum recycling and remelt secondary ingot production in the North America region. The models used to calculate the LCI are shown previously in **Figure 7-7** and **Figure 7-8**. The results of the LCI are shown in **Table 7-8**. The breakdowns of primary energy demand and carbon dioxide emissions for both scenarios are shown in **Table 7-9** and **Table 7-10**. Analysis of the two particular parameters is shown in the subsections followed.

It is important to emphasize the difference and their intended use between the two sets of data in the tables. One set reflects a ***recycling process*** with 100 percent of scrap as feedstock and no primary metals added. The product is recycled ingot or recovered aluminum. In contrast, the other set of data represents a common ***secondary production*** in which approximately **5 percent** of primary aluminum and alloying elements are added to make RSI. As the tables showing, energy demand and emissions for the two identical processes are different due to the involvement of primary aluminum.

Table 7-8: LCI of aluminum recycling and secondary aluminum production, representing 1000 kg of aluminum ingot

Inventory Category	**Aluminum Recycling (100% scrap)**	**Remelt Secondary Ingot (RSI, primary metal and alloy added)**
Energy (MJ)		
Non-renewable energy	8.66E+03	1.35E+04
Hydroelectric energy	3.82E+02	3.25E+03
Other renewable energy (except for hydro)	1.65E+02	2.29E+02
Resources (kg)		
Bauxite	3.51E+01	3.36E+02
Net fresh water (excluding energy)	4.29E+02	8.59E+02
Air Emissions (kg)		
Carbon dioxide	4.79E+02	9.21E+02
Carbon monoxide	1.62E-01	3.05E-01
Chlorine	9.89E-06	2.23E-05
Fluorine/Fluorides	2.35E-03	2.24E-02
Hydrogen chloride	5.76E-02	6.43E-02
Hydrogen fluoride	1.80E-02	3.83E-02
Nitrogen oxides	5.90E-01	1.31E+00
Nitrous oxide	3.77E-03	8.86E-03
Sulphur oxides	1.52E-16	2.24E-16
Non-methane VOCs	1.40E-01	1.98E-01
Methane	1.53E+00	2.14E+00
Dust (PM10)	1.18E-01	1.55E-01
Dust (PM2.5)	4.42E-02	1.55E-01
Fresh water Emissions (kg)		

Biological oxygen demand (BOD)	6.21E-03	7.10E-03
Chemical oxygen demand (COD)	1.09E-01	2.88E-01
Heavy metals	3.32E-01	2.65E+00
Ammonia	1.83E-04	2.45E-04
Fluorine/Fluorides	1.38E-02	1.05E-01
Phosphate	2.79E-04	5.19E-04
Solid waste (kg)		
Total waste (excluding mining overburden)	6.17E+01	2.82E+02

Table 7-9: Breakdown of primary energy demand and CO_2 emissions of aluminum recycling by unit processes, representing 1000 kg of recovered aluminum

Aluminum recycling (Recovered aluminum)					
Inventory parameter	**Unit**	**Scrap Processing, Melting and Casting**	**Dross & Salt Cake Recycling**	**Primary Ingot**	**Total**
Primary energy demand	GJ	9.14	0.04	0.000	9.18
Non-renewable	GJ	8.59	0.04	0.000	8.63
Renewable	GJ	0.54	0.00	0.000	0.55
CO2 emissions	MT CO2	0.48	0.00	0.000	0.48

Note: CO2 emissions represent one of the greenhouse gases. Total GHG emission results are shown in the LCIA results.

Table 7-10: Breakdown of primary energy demand and CO_2 emissions by unit processes for RSI production, representing 1000 kg of remelt secondary ingot

Remelt secondary aluminum ingot (RSI)					
Inventory parameter	**Unit**	**Scrap Processing, Melting and Casting**	**Dross & Salt Cake Recycling**	**Primary Ingot**	**Total**
Primary energy demand	GJ	9.14	0.04	7.51	16.68
Non-renewable	GJ	8.59	0.04	4.58	13.21
Renewable	GJ	0.54	0.00	2.92	3.47
CO2 emissions	MT CO2	0.48	0.00	0.43	0.91

Note: CO2 emissions represent one of the greenhouse gases. Total GHG emission results are shown in the LCIA results.

7.2.2.1 Primary Energy Demand

As it is shown in **Figure 7-9**, the majority of PED for aluminum recycling is associated with scrap processing and melting and casting. The two processes combined accounts for more than 99 percent of the total energy demand. Also showing in the figure is the majority (94 percent) of PED is from non-renewable energy source.

For RSI with 5 percent primary metal content (**Figure 7-10**), however, the addition of primary ingot contributes to **46 percent** of total energy demand and the melting and casting of metal contributes to the rest of the PED. Like the recycling scenario, the majority (79 percent) of energy is from non-renewable source.

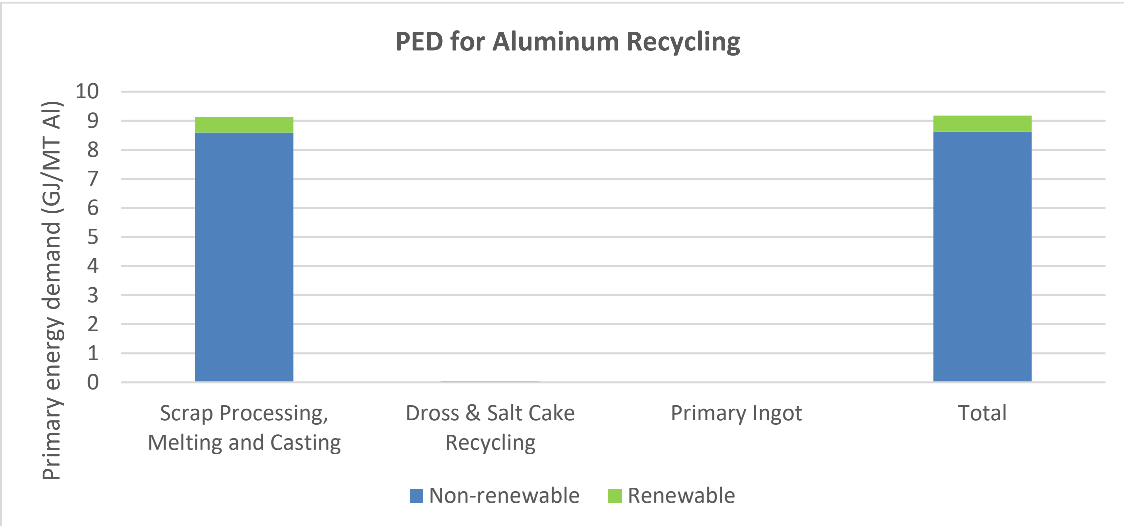

Figure 7-9: Primary energy demand of aluminum recycling, representing 1000 kg of recovered aluminum

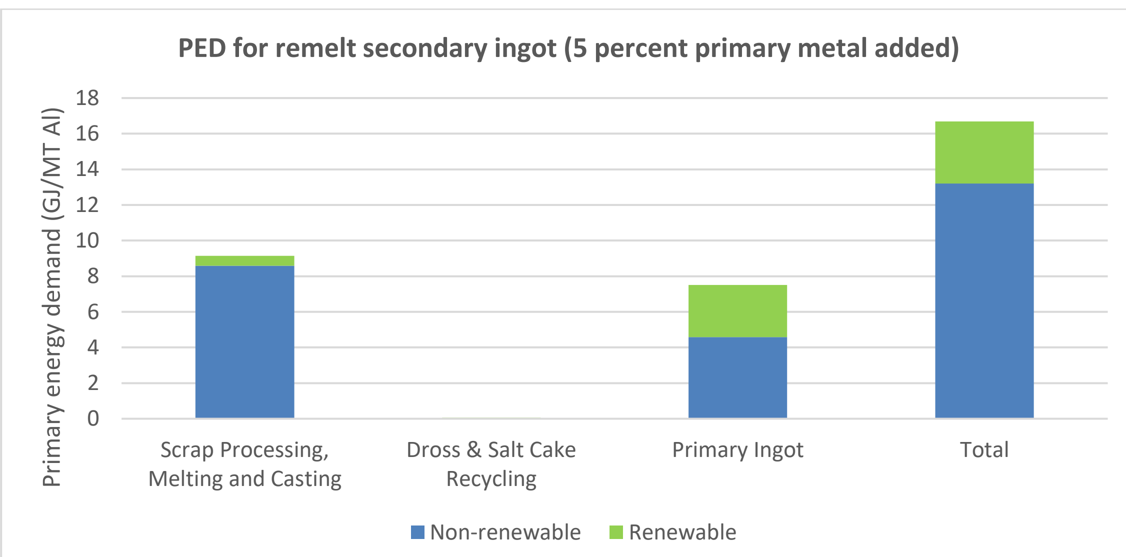

Figure 7-10: Primary energy demand of remelt secondary ingot production, representing 1000 kg of RSI

7.2.2.2 Carbon Dioxide Emissions

Like PED, as it is shown in **Figure 7-11**, the majority of CO_2 emissions for aluminum recycling is associated with the unit processes of scrap treatment, melting and casting. The two processes combined contributes more than 99 percent of the total emissions.

For RSI (**Figure 7-12**), however, the addition of only 5 percent primary ingot contributes to 47 percent of total CO_2 emissions and the rest attributes to scrap treatment and melting & casting operations.

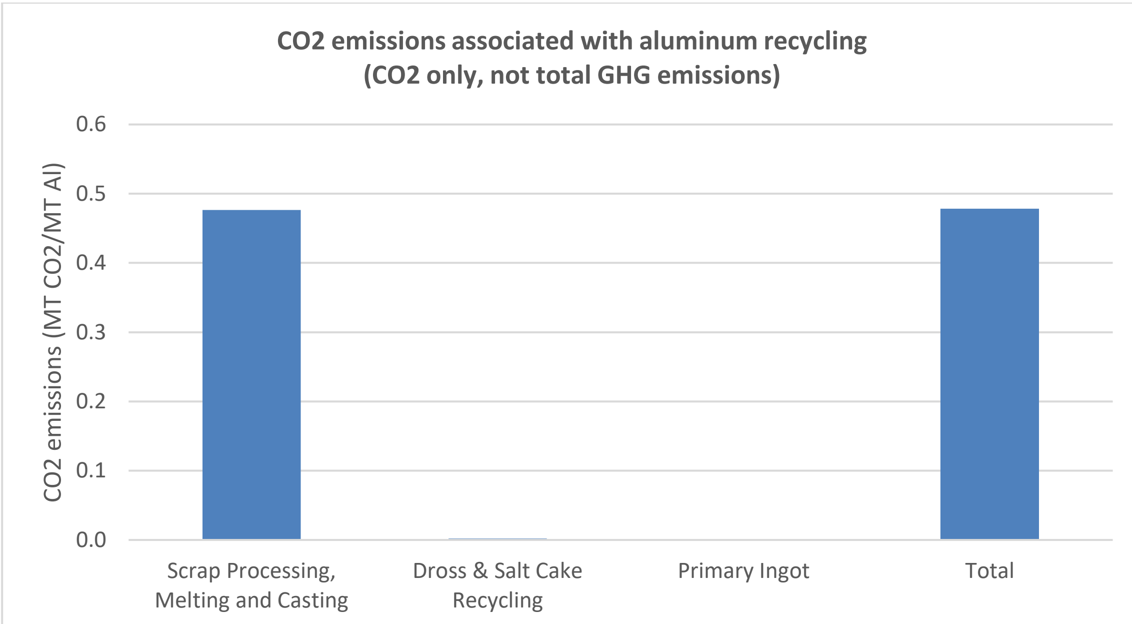

Figure 7-11: Carbon dioxide emissions associated with aluminum recycling, representing 1000 kg of recovered aluminum

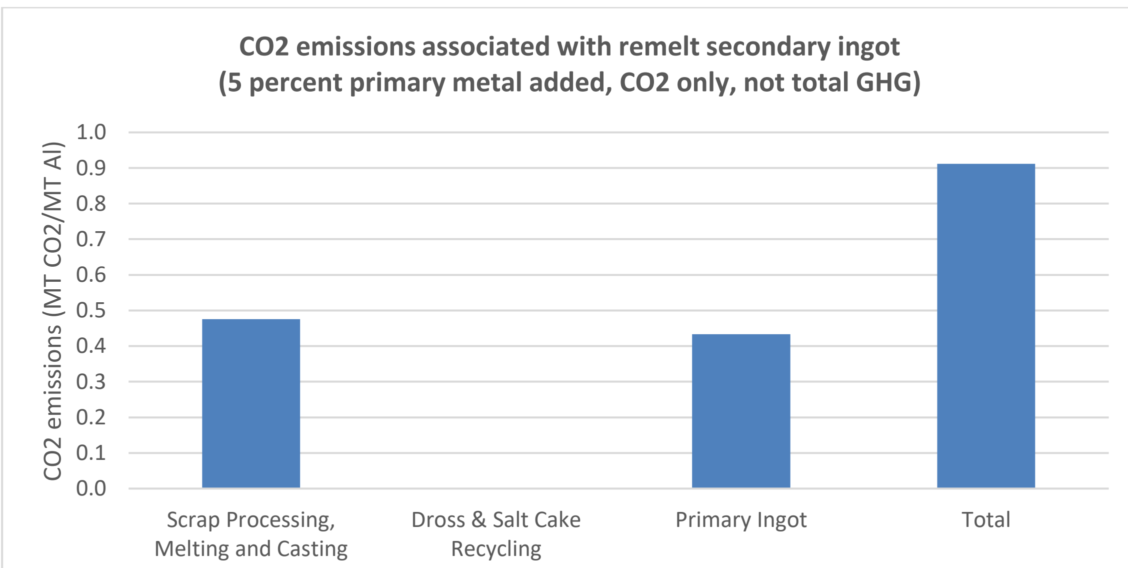

Figure 7-12: Carbon dioxide emissions associated with remelt secondary ingot production, representing 1000 kg of RSI

7.3 Aluminum Semi-Fabrication

7.3.1 Process Description and Models

Aluminum semi-fabrication is the process of transforming raw aluminum metal into an intermediate shape or profile so that it can be used to make a component of a product or a final product. Common semi-fabrication techniques include rolling, extrusion, casting, forging, and other methods. The processes and technologies involved are diversified. Production can be carried out in very large scale (in the case of rolling and extrusion) or as small as mom-and-pop shops (in the case of foundry/casting). In this report, we focus on three fabrication techniques and its products: extrusion, rolling and casting/foundry. Within each fabrication method, several subsets of products are included:

- Extrusion:
  - Extruded products for all applications
  - Extruded products for automotive applications
- Rolling:
  - Sheet for non-automotive and non-can applications
  - Sheet for automotive applications
  - Foil for all applications
- Casting:
  - Die casting for all applications including automotive

7.3.1.1 A Common Process: Ingot Preparation

The first step in semi-fabrication is metal preparation which is a process of turning raw metals – primary, recycled, as well as scrap – into specified alloys and desirable shapes of ingots. In the aluminum industry, this is known as a remelting & casting process. For large integrated companies, this step can be done internally, either at the same facility where semi-fabrication is carried out, or at an independent cast house operated by the same company. For small firms, this step can be carried out by a third party with the resulting ingots sold to the fabricator or through other means of contractual arrangements.

If the product is made of 100 percent primary aluminum, the remelting & casting process may be shortcut. A semi-fabricator could ask for a primary aluminum producer to cast specified semi-fabrication ingots directly from a smelter when the metal is still in molten stage and deliver them to the fabrication facility. By avoiding the remelting & casting process, this arrangement is more efficient than remelting the primary aluminum since it takes energy to remelt it. On the other hand, it will limit the ability of using scrap and recycled metal as feedstock since most smelters do not have scrap treatment capacity.

Ingots for extrusion are often known "billets" or "logs"; ingots for rolling are often called rolling ingots or "slabs"; and ingots for casting are simply called foundry ingots.

Aluminum Scrap | Aluminum Sow | Rolling Ingot

Figure 7-13: Metal source of a rolling facility

The remelting & casting process is essentially the same as it is illustrated previously in the secondary aluminum production process. Raw metals in the form of scrap or ingot are treated first to remove contaminants. It is subsequently charged into a melting furnace to turn it into molten metal, adding alloy elements to adjust it into a designated alloy, and casting it into a desirable shape. Ingot for extrusion is usually “log” or “bar” shaped. Ingot for rolling is often large and “slab” shaped. Ingot for casting is just shaped like a recycled ingot – also called a “sow”.

It is worth to note that there is no functional difference between a product made of primary aluminum and a product made of scrap or recycled aluminum. When alloyed to designated specifications, the product carries the same chemical composition regardless of its source of raw material. There is no testing method that can be used to detect if the product is made of primary or recycled metal. The only advantage for primary aluminum is it is usually unalloyed, thus providing more flexibility for making it a wide variety of desired alloys. On the other hand, both scrap and recycled aluminum themselves contain various levels of alloy elements and therefore make it harder to adjust to a desired specification.

Once semi-fabrication ingots are prepared, they will be processed into predefined shapes. A rolling process produces flat aluminum sheet, plate, or foil. An extrusion process produces various shapes and profiles. And a casting process produces shapes and profiles as well. It is worth to note that rolling and extrusion involve processing metal in solid form – often knowing as hot and cold working, while casting involves processing metal in molten form, thus requires an additional round of melting operation.

7.3.1.2 Metal Composition Information

Information on metal composition is crucial for recycle content disclosure and for accurately building LCA models. This section reports metal composition from both a recycle content disclosure and from a LCA model perspective for the examined product systems.

Users should be reminded about the difference between information for building LCA models and declaring recycled content. The key difference is the arbitrary exclusiveness of certain material input for recycled content declaration. This is reflected in both the ISO 14021 standards, and rules and regulations made by

various jurisdictions. For instance, ISO 14021 defines recycled content as "the proportion, by mass, of recycled material in a product or packaging. Only pre-consumer and post-consumer materials shall be considered as recycled content" Pre-consumer material is "material diverted from the waste stream during the manufacturing process. Excluded is the reutilization of materials such as rework, regrind or scrap generated in a process and capable of being reclaimed within the same process that generated it" (ISO 14021).

On the other hand, all material inputs must be included in the LCA models unless the quantities involved meet certain "cut-off" criteria. A LCA is an environmental footprint accounting in which all significant inputs and outputs must be accounted for to correctly reflect the true footprint of a product.

Information for recycled content declaration and a LCA model can be the same in many cases depending on how materials are classified, particularly in terms of internal versus pre-consumer scrap.

Metal composition information for this report was obtained though data survey by requiring survey respondents to report raw material feedstock by both scrap category and ingot category. Material mass-balance technique was used to verify accuracy and check errors and abnormalities.

During the data collection process, seven major feedstock categories were identified including primary metal, recycled metal, post-consumer (old) scrap, pre-consumer (new or post-industrial) scrap, mixed scrap, internal (run-around) scrap, and alloy elements. In addition, a few facilities reported molten metal – both primary and recycled – as feedstock. These were subsequently consolidated into their respective metal groups. The mixed scrap category refers to scrap metal in which the nature (old or new) of it can not be determined by visual impression since it is a mixture of both. Definitions of scrap categories are based on industry convention, and they are consistent with ISO 14021 (2006) standards and the related interpretation by UL Environment (UL, 2012).

7.3.1.2.1 Average Metal Composition for LCA Models

To build LCA models, aggregated survey results for metal inputs and outputs were used in its original format. All metals, in particular internal scrap, were included in the models. No input and output flows can be cut off without going through the strict cut off criteria test stated in Section **4.3.4**. Metal input information for the production of semi-fabrication ingot is listed in **Table 7-11** and **Table 7-12**.

Table 7-11: Metal inputs for generic semi-fabricated aluminum products, representing the production of 1,000 kg ingot for semi-fabrication

Metal Input Category	Generic Extrusion	Generic Sheet	Foil	Die Casting
Primary ingot/sow (kg)	399.21	210.06	210.06	209.00
Post-consumer scrap (kg)	165.40	131.07	131.07	N/A
Pre-consumer scrap (kg)	194.80	381.48	381.48	N/A
Mixed post and pre consumer scrap (kg)	246.64	144.33	144.33	N/A

Internal mill scrap (kg)	N/A	131.00	131.00	N/A
Recycled ingot/sow (kg)	17.05	36.66	36.66	836.00
Alloy elements (kg)	14.99	6.8	6.8	N/A
Total (kg)	1038.09	1041.40	1041.40	1045.00

Notes:

1. For die casting, it represents 1,000 kg of die cast products. No survey data was collected for die cast aluminum. The model in this study is built upon data from a study by the Die Cast Association. Metal composition is based on assumption following consultation from experts. Scrap categories are not applicable.
2. Generic extrusion and sheet products are normally shipped to the building & construction and consumer durables markets.
3. Metal composition data for aluminum foil was not obtained during the data survey process. This is because rolling ingot production facilities often cast a variety of ingots for different applications and thus have difficulty to differentiate metal feedstock for foil alone, which is usually a small proportion of those facility's outputs. In this study, metal composition for foil is assumed to be the same as generic sheet.

Table 7-12: Metal inputs for semi-fabricated automotive aluminum sheet and extrusion products, representing the production of 1,000 kg ingot for semi-fabrication

Metal Input Category	Automotive Sheet	Automotive Extrusion
Primary ingot/sow (kg)	519.77	275.75
Post-consumer scrap	0.00	166.41
Pre-consumer scrap (kg)	168.05	585.59
Mixed post and pre consumer scrap (kg)	N/A	N/A
Internal mill scrap (kg)	342.97	N/A
Recycled ingot/sow (kg)	0.00	0.00
Alloy elements (kg)	10.61	10.35
Total (kg)	1041.40	1038.10

Notes:

1. Application for extruded automotive products not only include passenger cars and light trucks, but also heavy trucks, truck trailers, and loading equipment. In other words, these products are used for all sorts of road vehicles.
2. No post-consumer scrap input for automotive sheet was reported. This is understandable since large scale of aluminum sheet application for automotive is relatively recent and the sheet in the vehicles is yet to be available for recycling (Zhu et al, 2020).

It is worth mentioning that internal mill scrap input is not applicable to extrusion products. For extrusion companies, billet production facility (remelting & casting facility) is considered as an independent manufacturing facility, and it is often not co-located with the extrusion facility. As a result, extrusion mill scrap is considered as a pre-consumer scrap – not an internal scrap input – by the billet casting facilities since casting and extrusion are considered distinctive processes.

In contrast, many rolling companies are integrated with a recycling capacity, and have the remelting & casting facilities co-located with their rolling mills. As a result, some companies consider rolling mill scrap as "internal scrap" if it can be utilized internally to produce new rolling ingots.

7.3.1.2.2 Average Metal Composition for Recycled Content Disclosure

In disclosing recycled content information for products, the ISO 14021 standard and the U.S. Federal Trade Commission's (FTC) Green Guides must be considered for compliance. For instance, the Green Guides generally prohibit internal scrap input to be used as part of the recycled content claim. In addition, recycled content information must be presented as a percentage. As a result, material input information collected from the LCA survey must be consolidated, and internal scrap must be removed from the recycled content calculation.

For this study and compliance with the FTC Green Guides, recycled content is calculated based on the same metal input information shown in **Table 7-11** and **Table 7-12** with internal scrap inputs excluded. Metal inputs are first consolidated from seven to four categories including primary metal (including newly added alloy elements), internal scrap, pre-consumer scrap, and post-consumer scrap. The following assumptions and treatments were made to consolidate metal inputs:

- Mixed scrap was split into old and new based on either additional information gathered through follow-ups with survey respondents, or an arbitrary 50/50 split when individual follow-up did not generate useful information;
- Recycled ingot was further split into old scrap, new scrap, and primary metal based either on answers to follow-up questions, or arbitrary assumptions when follow-up was not successful.

With information from the consolidated metal categories, the recycled content of an aluminum product was calculated with the following equations:

$$Postconsumer\ content\ (for\ recycled\ content\ declaration) = \frac{Postconsumer\ scrap\ input}{Total\ metal\ input - internal\ scrap\ input} \times 100\%$$

$$Preconsumer\ content\ (for\ recycled\ content\ declaration) = \frac{Preconsumer\ scrap\ input}{Total\ metal\ input - internal\ scrap\ input} \times 100\%$$

Note first that the equations effectively exclude internal scrap input from both the numerator and the denominator, i.e. internal scrap is assumed to be non-existing during the manufacturing process. Secondly, another important assumption is used to simplify the calculation. This is to assume the same metal loss rate during the remelting process for all input metals. This may not be true in real-world production. But such an assumption simplifies the calculation and will not affect the results in any significant way.

As a result, the calculated content for each of the product system is shown in three categories including primary metal (including newly added alloy elements), recovered metal from pre-consumer scrap, and recovered metal from post-consumer scrap. It is a weighted average of all relevant reporting facilities, based on their respective volume of semi-fabrication ingot production. The information is shown in **Table 7-13**.

Table 7-13: Metal composition information for recycled content declaration for semi-fabricated aluminum products in North America

Category of Metal Source	Generic Extrusion	Generic Sheet	Foil	Die Casting	Extrusion for Auto	Sheet for Auto
Primary metal (including new alloy elements), in percentage	39.9	23.8	23.8	20	27.6	75.9
Recovered metal from pre-consumer scrap, in percentage	31.5	51.8	51.8	N/A	56.4	24.1
Recovered metal from post-consumer scrap, in percentage	28.6	24.3	24.3	N/A	16.0	0

Note: Metal composition of die casting products was assumed to be 20 percent primary and 80 percent recycled metal. No assumption was made regarding to post and pre consumer proportions.

7.3.1.3 Extrusion

7.3.1.3.1 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 many dozens of 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 handling of process materials. The operations associated with this process include:

- Handling of cast extrusion 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;
- 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 manufacturer making components or final products.

7.3.1.3.2 Source of Raw Materials and Energy

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

As it is stated in **Section 7.1.1.4.4**, the large majority of primary metal consumed in North America is domestically produced, together with a small quantity of imports. For scrap and recycled aluminum, it is assumed that all is sourced domestically in 2016.

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 generation facility. In stead, they purchase their power from local utility companies.

7.3.1.4 Rolling

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 (DC) cast ingot or with continuous cast coils. Remelting & casting is often an integrated part of most rolled product producers. That process is elaborated in the previous ingot preparation section.

7.3.1.4.1 Hot-Rolling

7.3.1.4.1.1 Process Description

The purpose of rolling 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.

The process starts with either a DC cast ingot, also called a slab, or a continuous cast strip. A DC cast ingot is typically 18 to 30 inches thick and with a weight of 15 to 30 tons. Continuous cast strip is made directly from molten metal that solidifies into a continuous strip in one operation. A variety of methods are used to solidify the metal including roll casters, belt casters and block casters. It is estimated that about 20 percent of North American sheet and plate are produced through continuous casting, and the rest is produced through rolling of DC cast ingots.

Hot rolling is the method of rolling metal at a temperature high enough to avoid strain-hardening (work-hardening) as the metal is deformed. Ingots or strips 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 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. In some cases, hot rolled sheet or plate can be directly used to make the final product.

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 or coolant is an emulsion of water with about 5 percent of 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 raw materials to their storage areas on-site. The operations associated with this process include:

- Handling of rolling ingots, strips and ancillary materials;
- Breakdown rolling;
- Continuous 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, plate, or other form of intermediate rolling products (continuous casting products) that will be transported to an end-use customer or to a cold rolling and finishing facility.

7.3.1.4.1.2 Source of Raw Material and Energy

The source of major raw materials for this unit process is ingots. Similar to extrusion operations described in the previous section, all ingots 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. Unlike primary aluminum producers, most rolling facilities in North America do not purchase electricity from specific power generators, nor do they own any power generation facility. In stead, they purchase their power from local utility companies.

7.3.1.4.2 Cold-Rolling

7.3.1.4.2.1 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. 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, 2013).

In Summary, this unit process (as defined for this LCA study) begins with the handling of process materials. The operations associated with this process include:

- 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 that will be transported to an intermediate or end user.

7.3.1.4.2.2 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.

7.3.1.5 Die Casting

Aluminum casting, also called 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.

The three most important methods are die casting, permanent mold casting and sand casting. Such items as powertrains, transmissions, car engines and the cap atop the Washington Monument were all produced through the aluminum casting process (AA, Aluminum 101).

7.3.1.5.1 Source of Data

The Aluminum Association does not have good access to collect data from foundry companies. Efforts have been made but not successful. As a result, this study relies on secondary data from the GaBi database to model the production process, incorporating new data for raw materials in terms of primary and recycled ingots.

7.3.1.5.2 Die Casting as Representation

Due to data accessibility and data quality issues, this study focuses on die casting as a representation for all foundry products. Among the foundry products shipped in 2016, the share of die casting, permanent mold casting and sand casting was approximately 60%, 30% and 9%, respectively. Die casting thus represents two-thirds of the production volume.

7.3.1.5.3 Unit Process Description

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.

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

- 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 will be transported to a component or final product manufacturer.

7.3.1.5.4 Source of Raw Materials and Energy

The source of major raw materials for this unit process is primary and secondary aluminum ingots or aluminum scrap. 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. Similarly, it is assumed that unlike primary aluminum producers, most foundry facilities in North America do not purchase electricity from specific power generators, nor do they own any power generation facilities. In stead, they purchase their power from local utility companies.

7.3.2 LCI Results for Semi-Fabricated Products

This section presents the LCI results of semi-fabricated aluminum products in the North America region (**Table 7-14** and **Table 7-15**).

The "cradle-to-gate" LCI is represented by selected inventory parameters. The results are based on the actual mix of primary and recycled aluminum feedstocks for these products manufactured during 2016 except for automotive extrusion and automotive sheet, which represent the production years of 2018 and 2019, respectively. The models used to calculate the LCI are shown in **Figure 7-14**, **Figure 7-15**, **Figure 7-16**, **Figure 7-17**, **Figure 7-18** and **Figure 7-19**.

In addition, two of the most interesting LCI parameters – primary energy demand and CO_2 emissions – are presented in the "cradle-to-gate" format for users with different applications (**Table 7-16**). It is important to be noticed that the inventory of CO_2 emissions does not represent all GHG emissions. Total GHG emissions as the CO_2 equivalent are included in the LCIA results.

The two LCI parameters are also shown in **Figure 7-19** and **Figure 7-20**, respectively. Apparently, most of the primary energy demand for sei-fabricated products is met by non-renewable energy. This is largely due to fossil fuel electricity used for primary aluminum production, and natural gas used for the remelting & casting and semi-fabrication processes. CO2 emissions are almost exclusively attributed to fossil fuel energy supply (with a small proportion attributed to process chemical reactions of the electrolysis process).

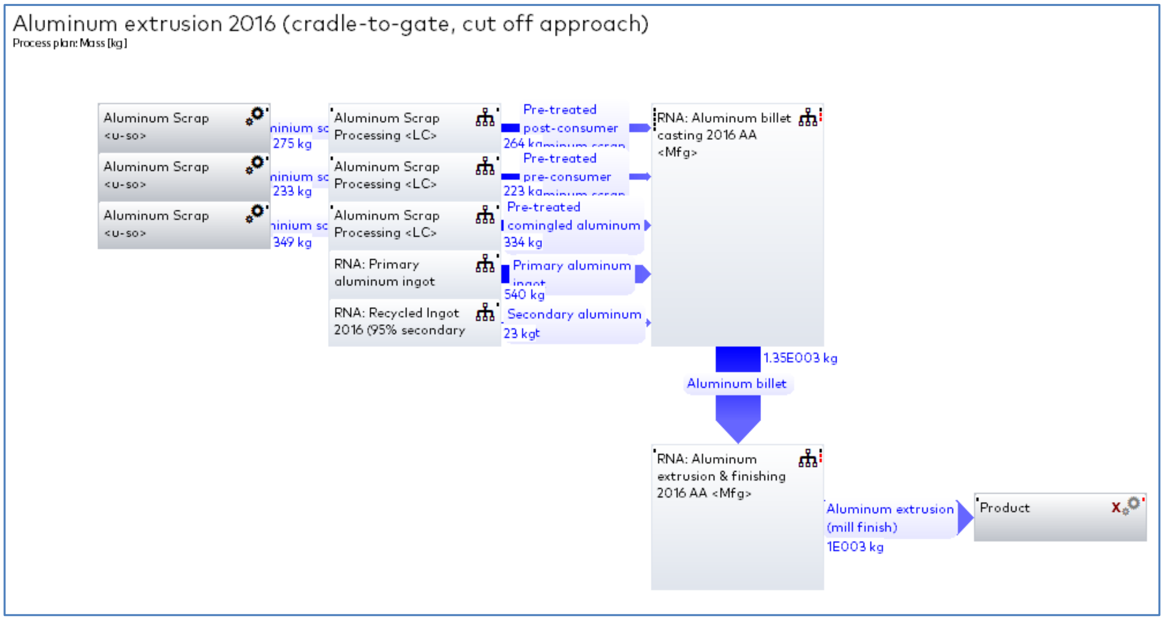

Figure 7-14: Illustration of the cradle-to-gate model for aluminum extrusion, representing 1,000 kg of aluminum extrusion products

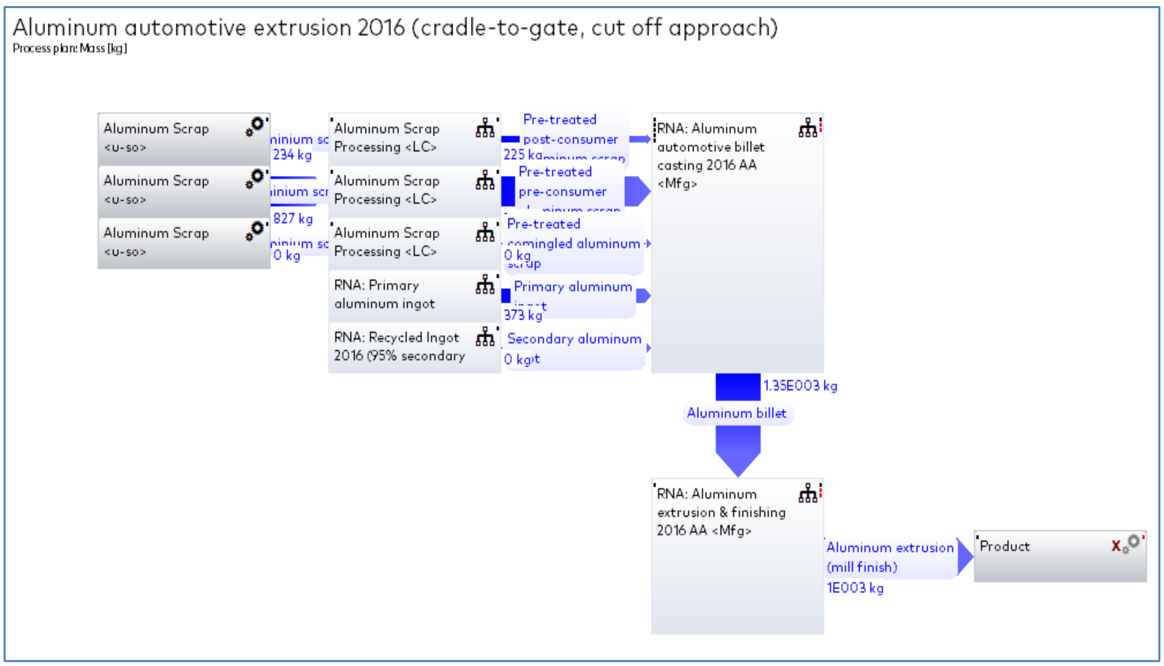

Figure 7-15: Illustration of the cradle-to-gate model for automotive aluminum extrusion, representing 1,000 kg of aluminum extrusion products

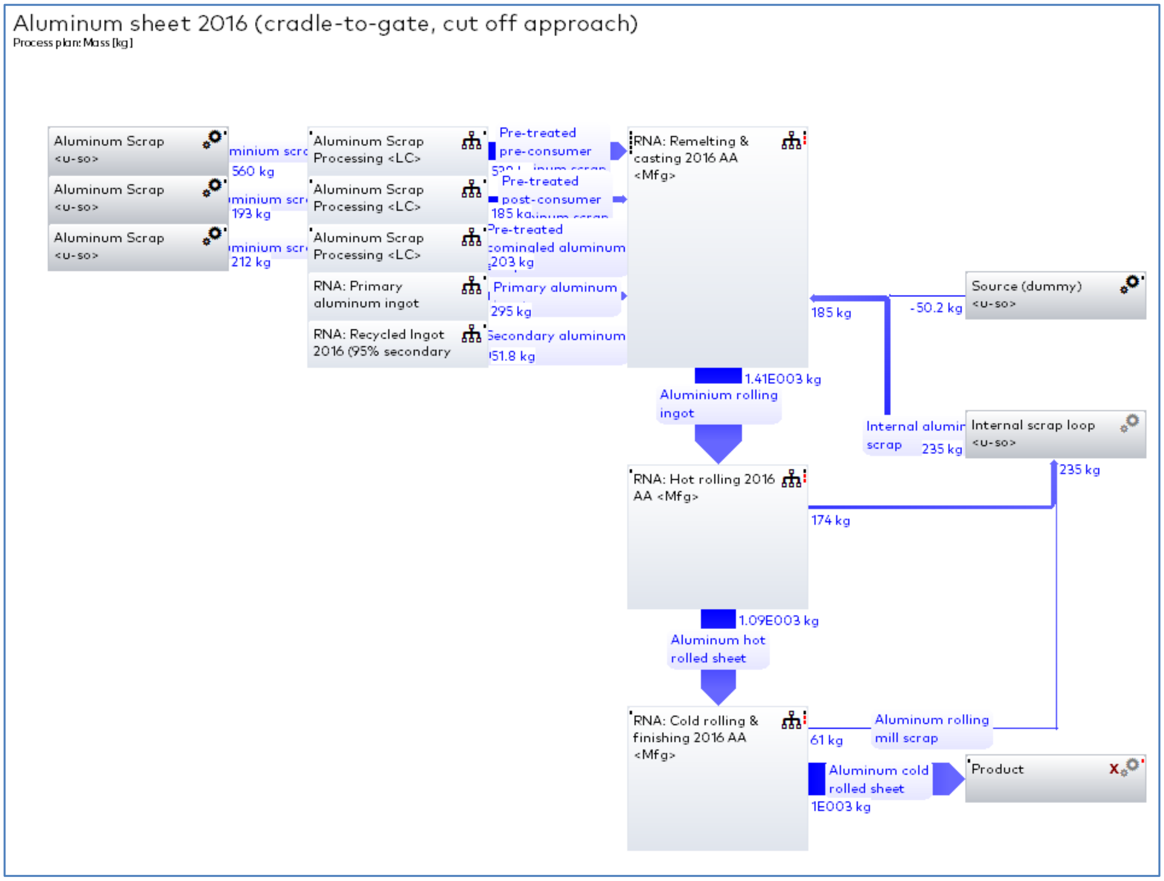

Figure 7-16: Illustration of the cradle-to-gate model for non-automotive, non-can aluminum sheet, representing 1,000 kg of aluminum sheet

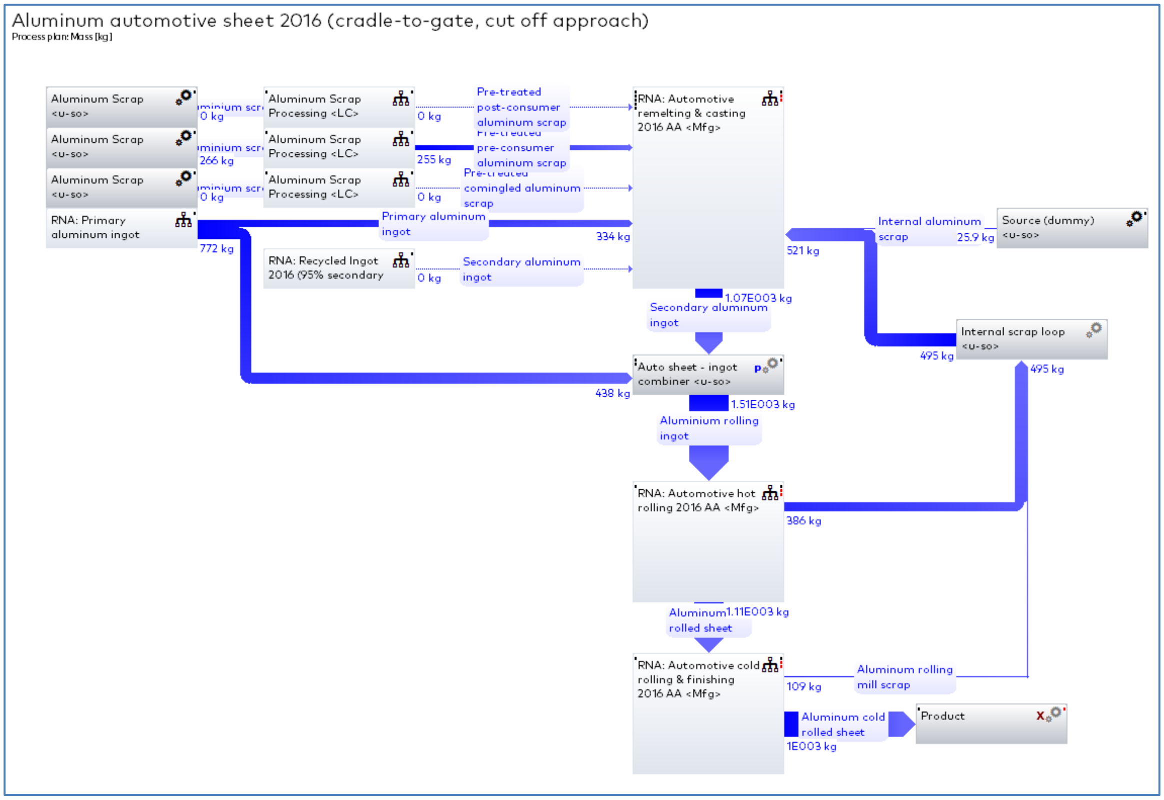

Figure 7-17: Illustration of the cradle-to-gate model for automotive aluminum sheet, representing 1,000 kg of aluminum auto sheet

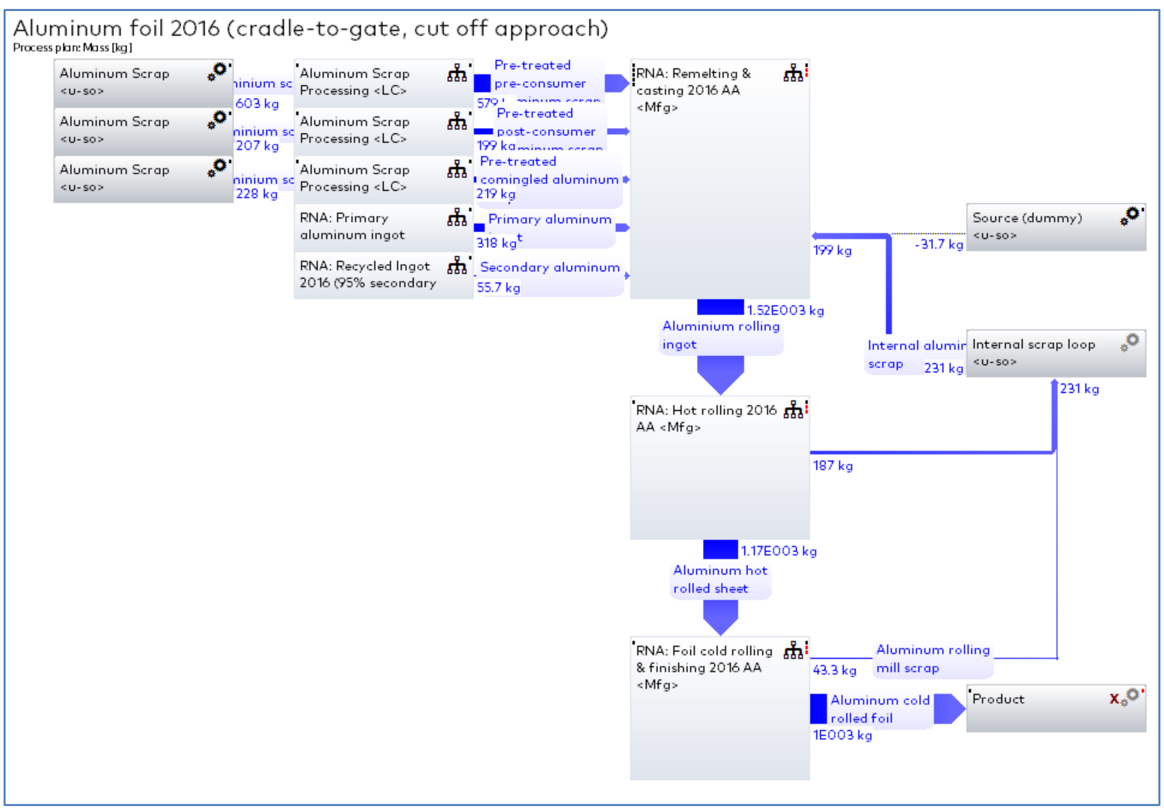

Figure 7-18: Illustration of the cradle-to-gate model for aluminum foil, representing 1,000 kg of aluminum foil

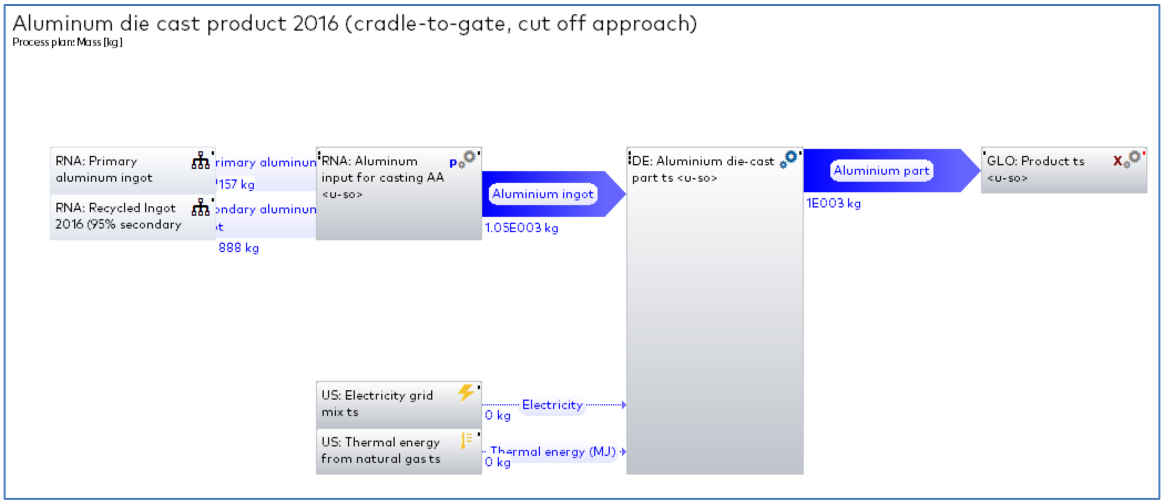

Figure 7-19: Illustration of the cradle-to-gate model for aluminum die casting, representing 1,000 kg of aluminum die cast products

Table 7-14: Cradle-to-gate LCI results of aluminum semi-fabrications, in selected parameters and representing 1,000 kg of fabricated products

Inventory Category	**Extruded Aluminum**	**Aluminum Sheet**	**Aluminum Foil**	**Cast Aluminum**
Energy (MJ)				
Non-renewable energy	7.10E+04	4.89E+04	5.89E+04	3.60E+04
Hydroelectric energy	2.94E+04	1.63E+04	1.77E+04	1.13E+04
Other renewable energy	1.92E+03	1.52E+03	2.22E+03	1.43E+03
Resources (kg)				
Bauxite	3.06E+03	1.68E+03	1.81E+03	1.15E+03
Net fresh water (excluding energy)	7.37E+03	4.89E+03	5.97E+03	3.54E+03
Air Emissions (kg)				
Carbon dioxide	5.71E+03	3.65E+03	4.27E+03	2.67E+03
Carbon monoxide	1.92E+00	1.17E+00	1.43E+00	9.05E-01
Chlorine	2.44E-04	2.62E-03	2.82E-03	5.56E-05
Fluorine/Fluorides	2.04E-01	1.12E-01	1.20E-01	7.69E-02
Hydrogen chloride	1.05E-01	1.28E-01	1.47E-01	9.30E-02
Hydrogen fluoride	2.14E-01	1.23E-01	1.33E-01	9.22E-02
Nitrogen oxides	8.67E+00	5.30E+00	6.05E+00	3.79E+00

Nitrous oxide	6.58E-02	4.31E-02	5.10E-02	3.11E-02
Sulphur oxides	1.60E-15	1.27E-15	1.71E-15	1.17E-15
Non-methane VOCs	1.13E+00	1.01E+00	1.20E+00	4.04E-01
Methane	9.88E+00	7.01E+00	8.47E+00	5.07E+00
Dust (PM10)	4.89E-01	4.09E-01	4.70E-01	2.43E-01
Dust (PM2.5)	1.18E+00	8.69E-01	9.51E-01	4.70E-01
Fresh water Emissions (kg)				
Biological oxygen demand (BOD)	6.10E-02	1.70E-02	1.44E-02	9.57E-03
Chemical oxygen demand (COD)	2.38E+00	1.54E+00	1.91E+00	1.25E+00
Heavy metals	2.40E+01	1.34E+01	1.46E+01	9.36E+00
Ammonia	1.86E-03	1.60E-03	2.28E-03	1.60E-03
Fluorine/Fluorides	9.53E-01	5.33E-01	5.84E-01	3.71E-01
Phosphate	3.55E-03	2.41E-03	3.05E-03	1.92E-03
Solid waste (kg)				
Total waste (excl. mining overburden)	2.33E+03	1.31E+03	1.42E+03	8.91E+02

Table 7-15: Cradle-to-gate LCI results of automotive sheet and extrusions, in selected parameters and representing 1,000 kg of products

Inventory Category	**Automotive Extruded Aluminum**	**Automotive Aluminum Sheet**
Energy (MJ)		
Non-renewable energy	5.67E+04	8.36E+04
Hydroelectric energy	2.04E+04	4.06E+04
Other renewable energy (except for hydro)	1.76E+03	1.87E+03
Resources (kg)		
Bauxite	2.11E+03	4.24E+03
Net fresh water (excluding energy)	6.08E+03	8.11E+03
Air Emissions (kg)		
Carbon dioxide	4.35E+03	7.12E+03
Carbon monoxide	1.47E+00	2.35E+00
Chlorine	2.05E-04	2.12E-03
Fluorine/Fluorides	1.40E-01	2.82E-01

Hydrogen chloride	8.32E-02	1.63E-01
Hydrogen fluoride	1.49E-01	2.93E-01
Nitrogen oxides	6.42E+00	1.11E+01
Nitrous oxide	5.02E-02	8.32E-02
Sulphur oxides	1.38E-15	1.76E-15
Non-methane VOCs	9.59E-01	1.42E+00
Methane	8.11E+00	1.11E+01
Dust (PM10)	3.70E-01	7.00E-01
Dust (PM2.5)	8.31E-01	1.79E+00
Fresh water Emissions (kg)		
Biological oxygen demand (BOD)	5.84E-02	2.26E-02
Chemical oxygen demand (COD)	1.84E+00	2.95E+00
Heavy metals	1.67E+01	3.30E+01
Ammonia	1.72E-03	1.89E-03
Fluorine/Fluorides	6.65E-01	1.30E+00
Phosphate	2.83E-03	4.23E-03
Solid waste (kg)		
Total waste (excluding mining overburden)	1.64E+03	3.15E+03

Table 7-16: Cradle-to-gate primary energy and CO_2 emission results of aluminum semi-fabrications, representing 1000 kg of fabricated products

Semi-fabricated products (cradle-to-gate)							
Inventory parameter	**Unit**	**Extrusion**	**Sheet**	**Foil**	**Cast**	**Auto Extrusion**	**Auto Sheet**
Primary energy demand	GJ	102.378	66.723	78.871	48.755	78.970	126.14
Non-renewable	GJ	71.005	48.887	58.935	35.980	56.788	83.64
Renewable	GJ	31.373	17.836	19.936	12.775	22.182	42.50
CO2 emissions	MT CO2	5.708	3.651	4.272	2.666	4.350	7.12

Note: CO2 emissions represent one of the greenhouse gases. Total GHG emission results are shown in the LCIA results.

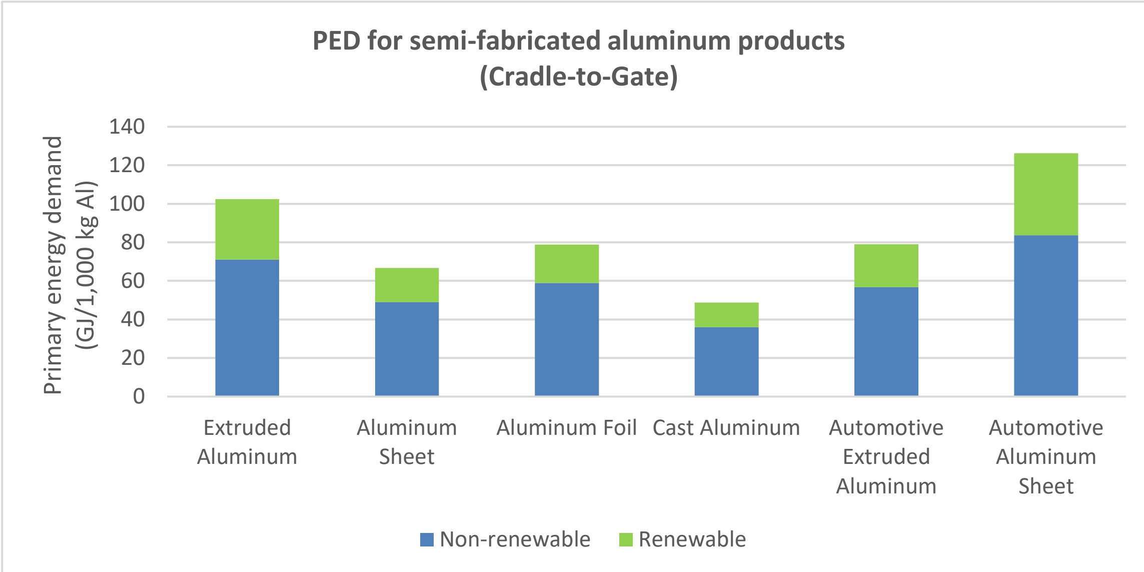

Figure 7-20: Breakdown of cradle-to-gate primary energy demand for semi-fabricated aluminum products, representing 1,000 kg of aluminum products

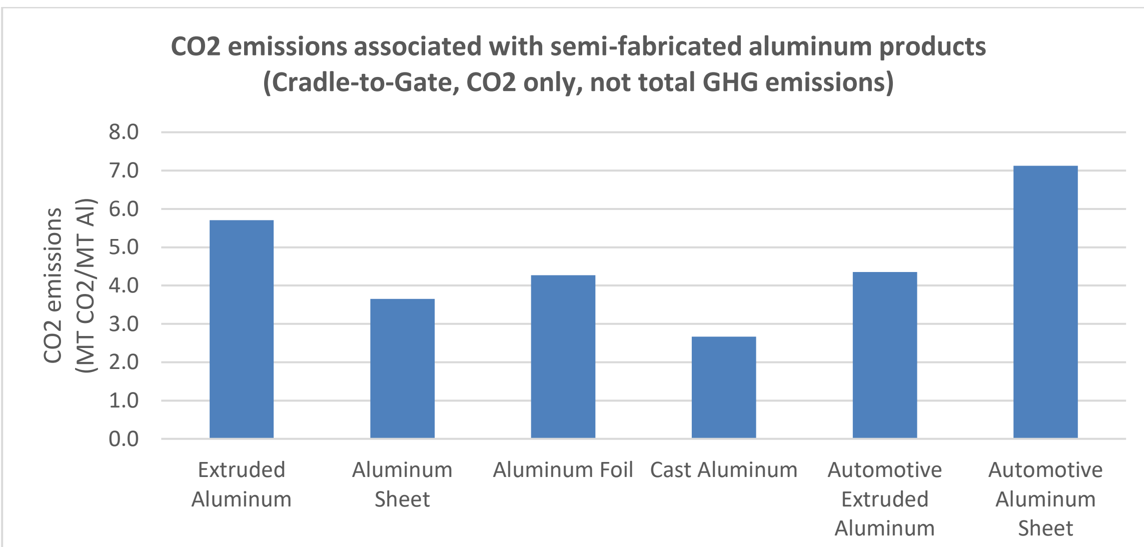

Figure 7-21: Cradle-to-gate CO_2 emissions for semi-fabricated aluminum products, representing 1,000 kg of aluminum products

8. Life Cycle Impact Assessment Results

8.1 Primary Aluminum

In this section, the Life Cycle Impact Assessment (LCIA) results are presented – in the format of domestic production and consumption mix – for 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 LCIs.

As described in **Section 5.2** of this report, the impact assessment results were calculated using characterization factors of TRACI 2.1 published by the U.S. EPA and IPCC AR5.

The results of LCIA are shown in **Table 8-1** and **Table 8-2**. Explanation and analysis on each of the impact categories are shown in the subsections followed.

Table 8-1: Cradle-to-gate LCIA results for production of 1,000 kg of domestic primary aluminum in North America

Assessment parameter	Unit	Bauxite mining	Alumina refining	Electrolysis	Cast house	Total
Primary energy demand	GJ	0.61	32.87	99.93	1.91	135.32
Global warming potential	kg CO2e	48.49	2801.58	5489.62	115.62	8455.31
Acidification potential	kg SO2e	0.24	10.96	25.54	0.25	36.99
Eutrophication potential	kg Ne	0.01	0.47	0.33	0.01	0.82
Smog formation potential	kg O3e	2.81	184.31	81.35	5.40	273.87

Table 8-2: Cradle-to-gate LCIA results for the consumption mix of 1,000 kg primary aluminum ingot in North America, represented by each production region

Assessment parameter	Primary energy demand (GJ)	Global warming potential (kg CO2 eq.)	Acidification potential (kg SO2 eq.)	Eutrophication potential (kg N eq.)	Smog formation potential (kg O3 eq.)
North America	109.88	6865.71	30.03	0.67	222.38
Russia	12.81	639.65	3.43	0.08	38.65
U.A.E.	5.62	423.68	2.11	0.06	33.52
Argentina	2.71	193.28	0.99	0.02	8.27
Venezuela	1.04	73.93	0.38	0.01	3.16
Bahrain	0.48	36.04	0.18	0.01	2.85

Brazil	0.41	29.09	0.15	0.00	1.25
Rest of World	2.75	253.14	1.35	0.04	16.08
Total	**135.69**	**8514.52**	**38.62**	**0.88**	**326.17**

8.1.1 Acidification Potential

The acidification potential is a measurement 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 1,000 kg of primary aluminum ingot production in North America amounts to **37 kg SO_2 equivalent** (**Table 8-1**).

Breaking the emissions down by production stages shows that the **electrolysis process** is responsible for **69 percent** of the total acidification potential result; followed by **alumina refining** which has a **30 percent** contribution (**Figure 8-1**).

Comparing to the results of the 2013 study, the industry has witnessed a **34 percent reduction** from the production year of 2010 to 2016. Most of the acidification impacts are associated with upstream emissions during **electricity generation** and the improvement is attributed to the reduction of coal fired power.

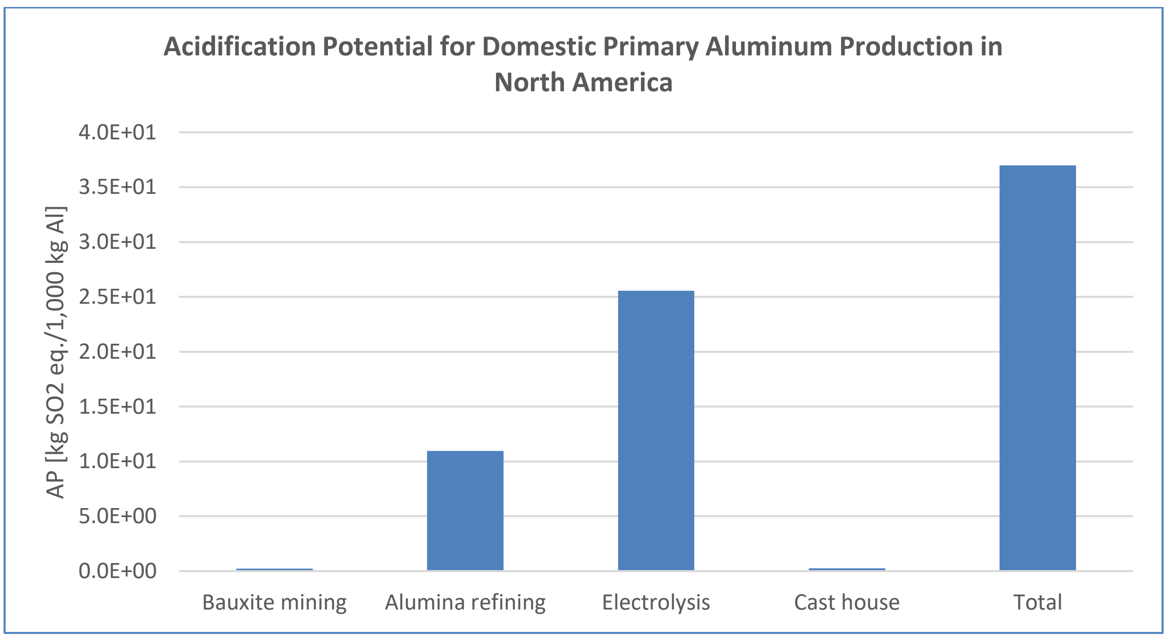

Figure 8-1: Acidification potential results for domestic primary aluminum ingot production.

8.1.2 Eutrophication Potential

The eutrophication potential is a measurement 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 **0.82 kg Nitrogen equivalent** (**Table 8-1**). 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 8-2** shows that the **alumina refining and electrolysis processes** together are responsible for **98 percent** of the eutrophication impacts result, with individual contributions of 57 percent and 41 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.

Comparing this study to the previous one, a **15 percent reduction** in eutrophication potential has been achieved for domestic primary aluminum production in North America from 2010 to 2016.

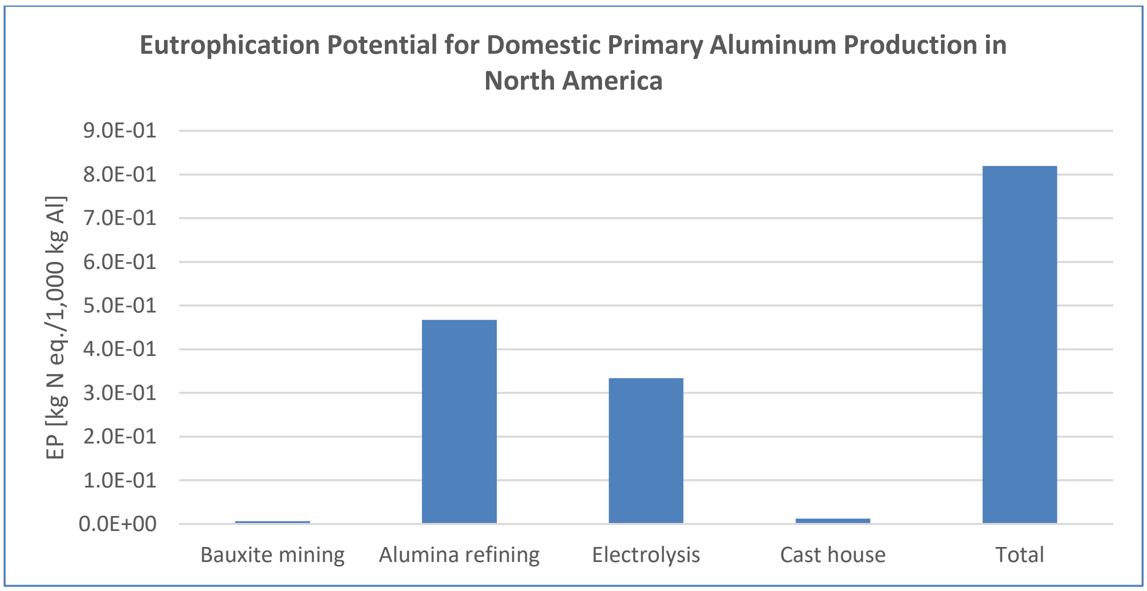

Figure 8-2: Eutrophication potential results for domestic primary aluminum production.

8.1.3 Global Warming Potential (100 Years)

The Global Warming Potential (GWP) is a measurement 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 1,000 kg of primary aluminum ingot in North America is **8,455 kg CO_2 equivalent** (**Table 8-1**).

A breakdown of the GWP impact by component greenhouse gases shows that almost 93 percent of the net GWP comes from CO_2, 4 percent from Tetrafluoromethane (CF_4), 1 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 8-3** and it shows that **65 percent** of the global warming impacts come from the **electrolysis process**. **Alumina refining** is next largest contributor with a **33 percent** share of net global warming potential. The rest is attributed to mining and cast house operations.

The share of global warming potential from direct greenhouse gas emissions is approximately **47 percent** of net GWP impact, while indirect CO_2 emissions (mainly from electricity production) account for another **53 percent** of net GWP impact.

Comparing to the results of the 2013 study, the industry has witnessed a **5 percent reduction of GWP from the production year 2010 to 2016**. Such reduction is mostly attributed to the increased share of renewable electricity usage and decreased share of coal-fired electricity usage for smelting.

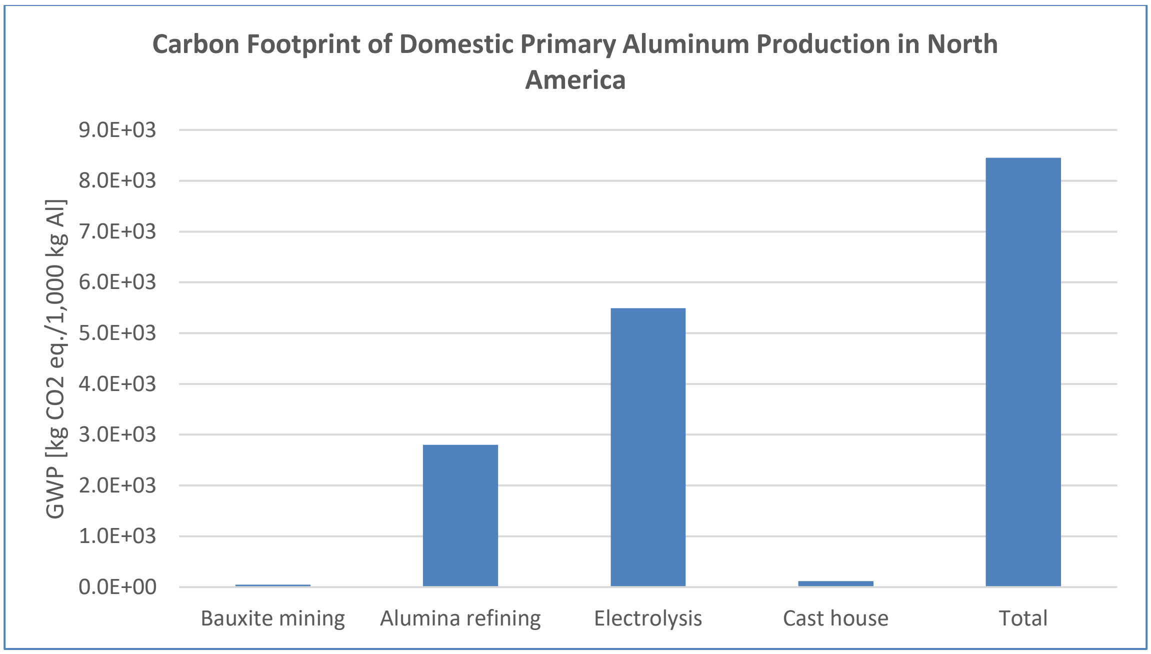

Figure 8-3: Global warming potential results for domestic primary aluminum production.

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

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

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 8-3**.

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, 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 8-3: Scope 1, 2, and 3 GHG emissions for domestic primary aluminum ingot production, representing 1000 kg of primary aluminum ingot

Production Stage	Scope 1	Scope 2	Scope 3	Total
Bauxite (ton CO2eq/ton Al)	0.04	0.01	0.00	0.05
Alumina (ton CO2eq/ton Al)	2.11	0.17	0.53	2.81
Electrolysis (ton CO2eq/ton Al)	1.77	3.23	0.50	5.50
Cast house (ton CO2eq/ton Al)	0.08	0.03	0.01	0.12
Total (ton CO2eq/ton Al)	3.99	3.43	1.03	8.45

8.1.4 Smog Formation Potential

The Smog Formation Potential (SFP) 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. SFP is expressed as kg ozone (O_3) equivalent.

The SFP results are illustrated in **Figure 8-4** as well as in **Table 8-1**. The SFP related to the production of one metric ton of primary aluminum in North America is 273.9 kg O_3 equivalent. Smog formation potential for primary aluminum comes from NO_x emissions, which account for 99 percent of the SFP impact.

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

Alumina refining is responsible for **67 percent** of the net smog creation impact, followed by the **electrolysis process,** which accounts for **30 percent** of the total SFP.

From 2010 to 2016, the industry has achieved a **38 percent reduction** in SFP.

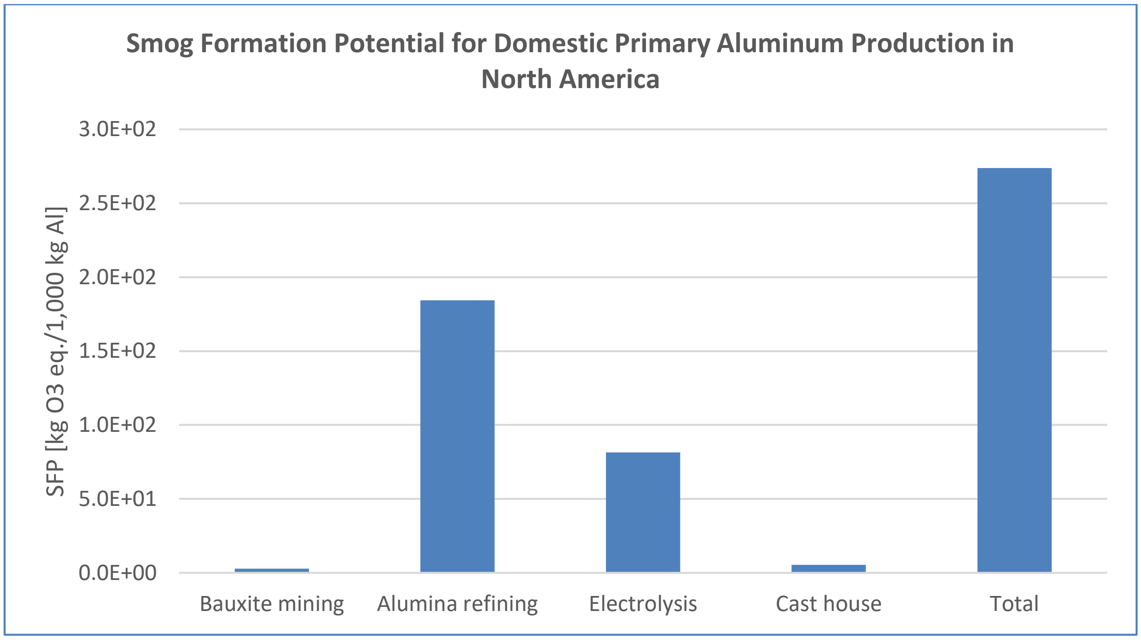

Figure 8-4: Smog formation potential results for primary aluminum ingot production.

8.2 Recycled Aluminum

The LCIA results of aluminum recycling and remelt secondary aluminum ingot are presented in **Table 8-4** and **Table 8-5**, respectively. The results represent the output of 1,000 kg of metal in North America.

It is again worth to reminder the difference between **Table 8-4** and **Table 8-5**. While **Table 8-4** refers to recycling with 100 percent scrap as feedstock, **Table 8-5** represents the production of RSI with an addition of approximately 5 percent of primary aluminum and alloying elements.

When users try to decide which table to choose for their data needs, they should keep in mind what is the ultimate purpose. For instance:

- if a user knows the "recycled content" of a product and intends to estimate the environmental footprint of the product, **Table 8-4** shall be used;
- similarly, if a user is focusing on recycling and wants to find the footprint for recycling or the "benefit" of recycling, **Table 8-4** shall be used;
- on the other hand, if a user is dealing with RSI which is tailer-made for a customer with the addition of 5 percent primary aluminum, **Table 8-5** shall be used;
- the bottom-line for data selection is to avoid ***double counting*** of primary aluminum.

Table 8-4: LCIA results for aluminum recycling, representing 1000 kg of recovered aluminum in North America

Assessment Parameter	Unit	Scrap Processing, Melting and Casting	Dross & Salt Cake Recycling	Primary Ingot	Total
Primary energy demand	GJ	9.14	0.04	0.00	9.18
Global warming potential	kg CO2e	524.59	2.13	0.00	526.71
Acidification potential	kg SO2e	0.86	0.00	0.00	0.87
Eutrophication potential	kg Ne	0.04	0.00	0.00	0.04
Smog formation potential	kg O3e	15.56	0.08	0.00	15.64

Table 8-5: LCIA results for remelt secondary aluminum ingot production, representing 1000 kg of RSI in North America

Assessment Parameter	Unit	Scrap Processing, Melting and Casting	Dross & Salt Cake Recycling	Primary Ingot	Total
Primary energy demand	GJ	9.14	0.04	7.51	16.68
Global warming potential	kg CO2 eq.	524.59	2.13	471.00	997.71
Acidification potential	kg SO2 eq.	0.86	0.00	2.14	3.00
Eutrophication potential	kg N eq.	0.04	0.00	0.05	0.09
Smog formation potential	kg O3 eq.	15.56	0.08	18.04	33.68

Clearly, the scrap treatment, melting and ingot casting step is responsible for most of the environmental impacts for both recycling and RSI production. The recycling of dross and salt cake has a minor share since the quantity is relatively small. The input of primary aluminum for RSI production can drastically change the total footprint. In the case of this study, an addition of 5 percent primary aluminum almost leads to a double of the total footprint.

Comparing to the previous study, the overall environmental footprint of aluminum recycling has been reduced. For instance, the primary energy demand has been reduced **16 percent** and carbon footprint has been reduced **21 percent**. The improvement may be attributed to improved efficiency across the industry. However, the exact causes of such reduction still need to be further explored since we have seen fluctuations on these results over the past decades.

8.3 Semi-Fabricated Aluminum Products

This section presents the LCIA results of semi-fabricated aluminum products manufactured 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-gate” results are shown in **Section 7.3.2** and the models used to calculate the “cradle-to-grave” results are shown in **Figure 8-5**, **Figure 8-6**, **Figure 8-7**, **Figure 8-8**, **Figure 8-9**, and **Figure 8-10**.

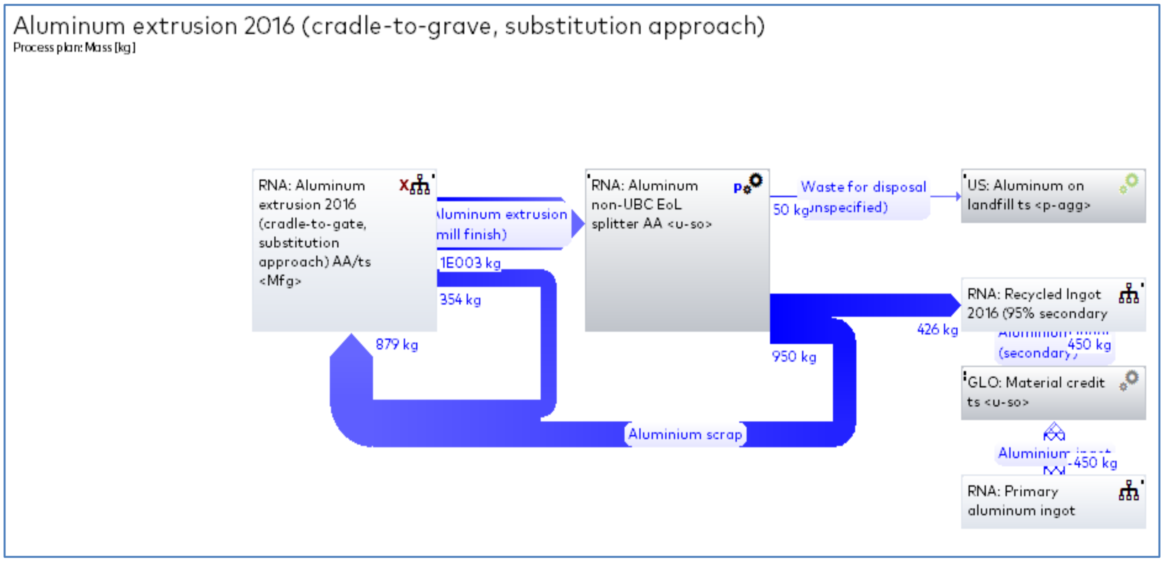

Figure 8-5: Illustration of the cradle-to-grave model for aluminum extrusion, representing 1000 kg of aluminum extrusion products

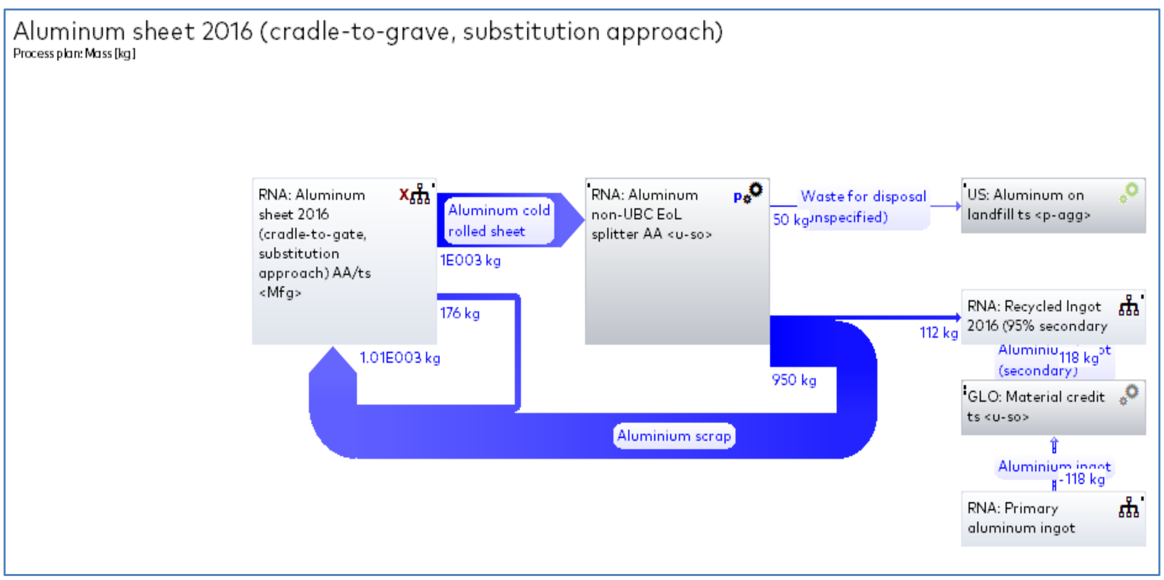

Figure 8-6: Illustration of the cradle-to-grave model for aluminum sheet, representing 1000 kg of aluminum sheet products

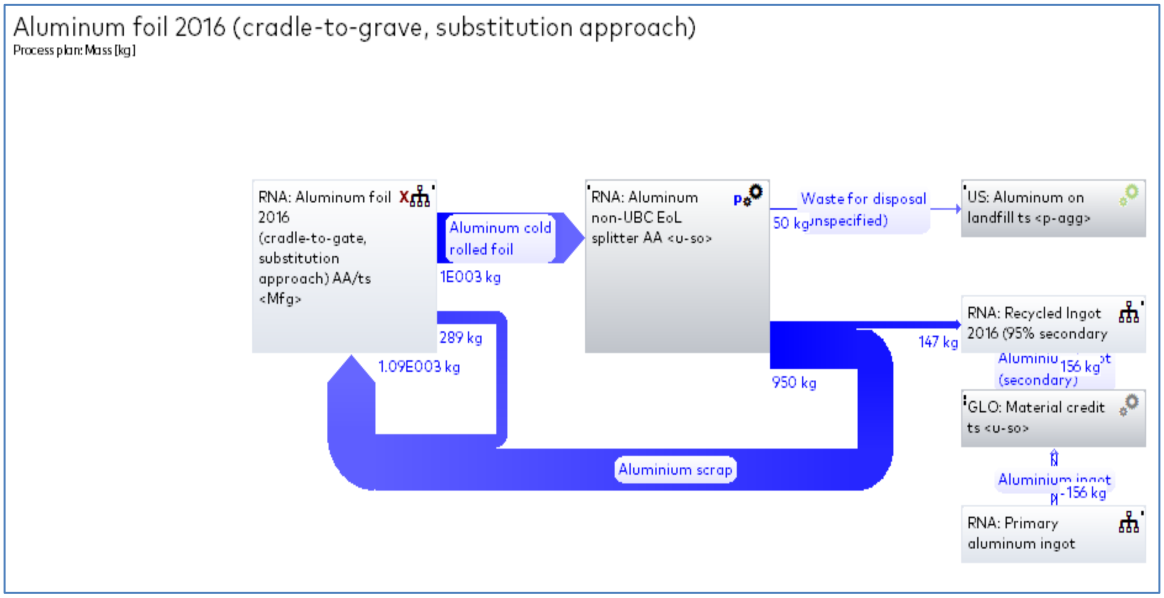

Figure 8-7: Illustration of the cradle-to-grave model for aluminum foil, representing 1000 kg of foil products

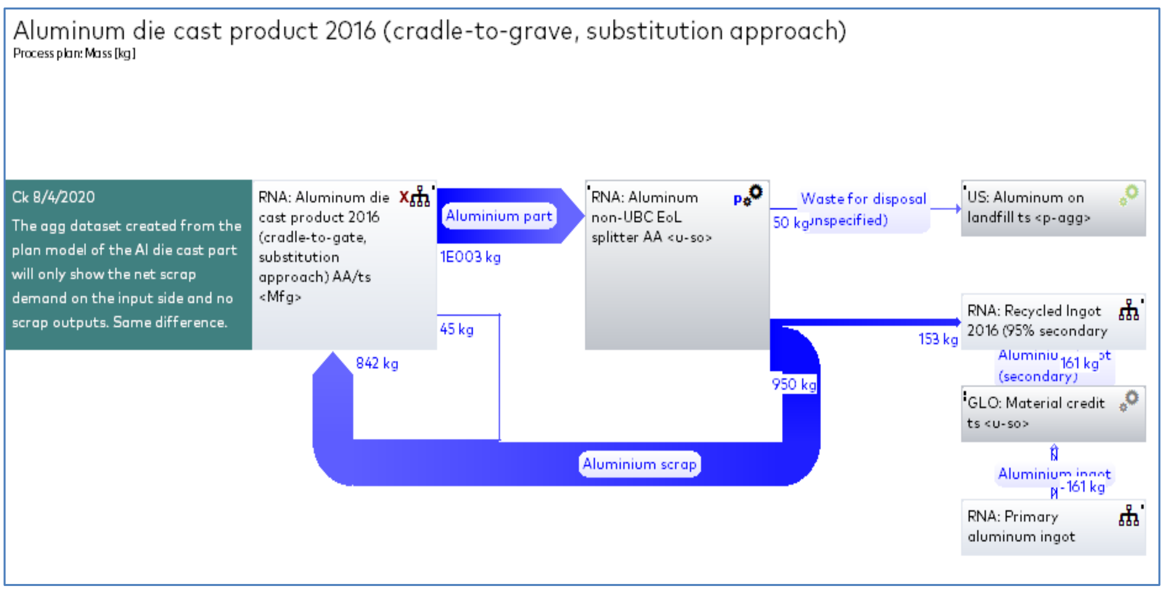

Figure 8-8: Illustration of the cradle-to-grave model for aluminum die casting, representing 1000 kg of die cast products

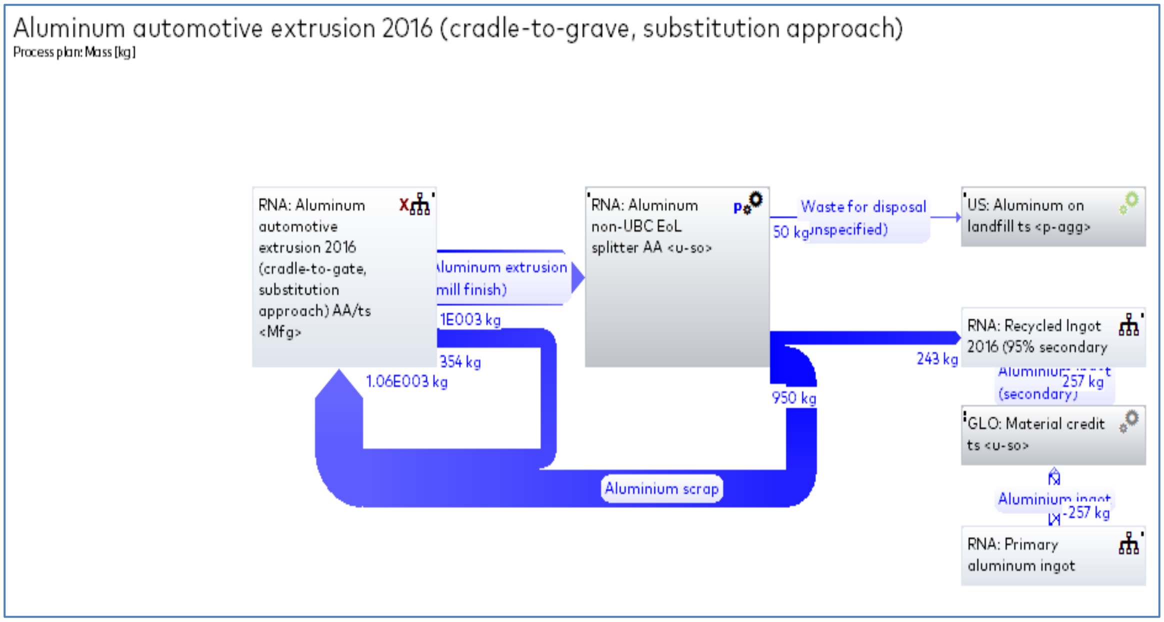

Figure 8-9: Illustration of the cradle-to-grave model for aluminum extrusion for automotive applications, representing 1000 kg of automotive extrusion products

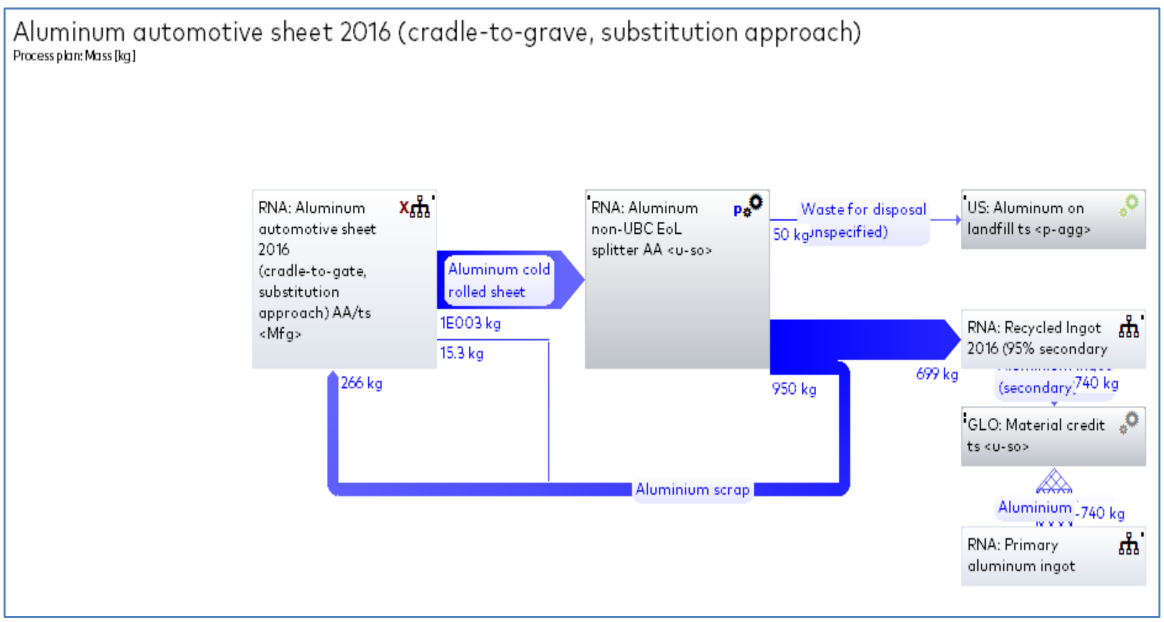

Figure 8-10: Illustration of the cradle-to-grave model for aluminum sheet for automotive applications, representing 1000 kg of automotive sheet products

The Cradle-to-Gate LCIA results of the examined semi-fabricated product systems are shown in **Table 8-6**. Information for breakdown of the results by manufacturing processes for each product system is listed in the **Appendix** (**12.3.1**).

Table 8-6: Cradle-to-gate LCIA results of semi-fabricated aluminum products, representing 1,000 kg of products

Assessment Parameter	Extrusion	Sheet	Foil	Die Cast	Automotive Extrusion	Automotive Sheet

Primary energy demand (GJ)	102.38	66.72	78.87	48.76	78.97	126.14
Global warming potential (kg CO2 e.)	6213.22	3978.32	4653.41	2898.98	4739.43	7744.79
Acidification potential (kg SO2 e.)	23.77	13.81	15.39	9.66	17.04	31.68
Eutrophication potential (kg N e.)	0.64	0.39	0.46	0.28	0.49	0.79
Smog formation potential (kg O3 e.)	225.73	140.21	159.59	96.23	169.01	287.04

The Cradle-to-Grave LCIA results of the examined semi-fabricated product systems are shown in **Table 8-7**. Information for breakdown of the results by manufacturing processes for each product system is listed in the **Appendix** (**0**).

The results are based on the assumption of a 95 percent recycling rate at the end-of-life. A recycling rate of 95 percent or more 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 product finishing and 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 8-7: Cradle-to-grave LCIA results of semi-fabricated aluminum products assuming 95 percent recycling rate, representing 1,000 kg of products

Assessment Parameter	Extrusion	Sheet	Foil	Die Cast	Automotive Extrusion	Automotive Sheet
Primary energy demand (GJ)	46.28	49.79	57.30	29.25	45.93	35.96
Global warming potential (kg CO2 e.)	2667.42	2903.98	3286.18	1666.76	2649.77	2044.85
Acidification potential (kg SO2 e.)	6.99	8.74	8.94	3.82	7.16	4.69
Eutrophication potential (kg N e.)	0.27	0.28	0.32	0.16	0.27	0.19
Smog formation potential (kg O3 e.)	88.04	98.75	106.75	48.38	87.98	65.54

9. Interpretation and Conclusion

This study provides an update to a similar report published in 2013 and quantifies the latest environmental footprint for primary aluminum, recycled aluminum, and semi-fabricated aluminum products manufactured in North America. The production year for the baseline scenario is 2016.

The environmental footprint is indicated by the LCI and LCIA of the product categories. It 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 a net scrap substitution approach.

9.1 Cradle-to-Gate

9.1.1 Energy Demand Key Driver of Environmental Footprint

From a ***cradle-to-gate*** perspective, most of the environmental footprint of the examined product systems is energy related. The generation of electricity, particularly from fossil fuel fired power plants, attributes to the largest share of the total footprint.

The attribution of electricity to the overall footprint is directly related to the use of primary aluminum as a feedstock. Although primary aluminum is only a small share of the raw material input in many of the examined product systems, it nevertheless accounts for **more than 40 percent** of the environmental impact for most of the products (**Figure 9-1** and **Figure 9-2**). The remelting & casting process, which melts scrap and raw metal to produce fabrication ingots, is the next footprint intensive process, followed by semi-fabrication such as rolling and extrusion. A detailed breakdown of the results by manufacturing processes for each product system is listed in the **Appendix** (**12.3.1**).

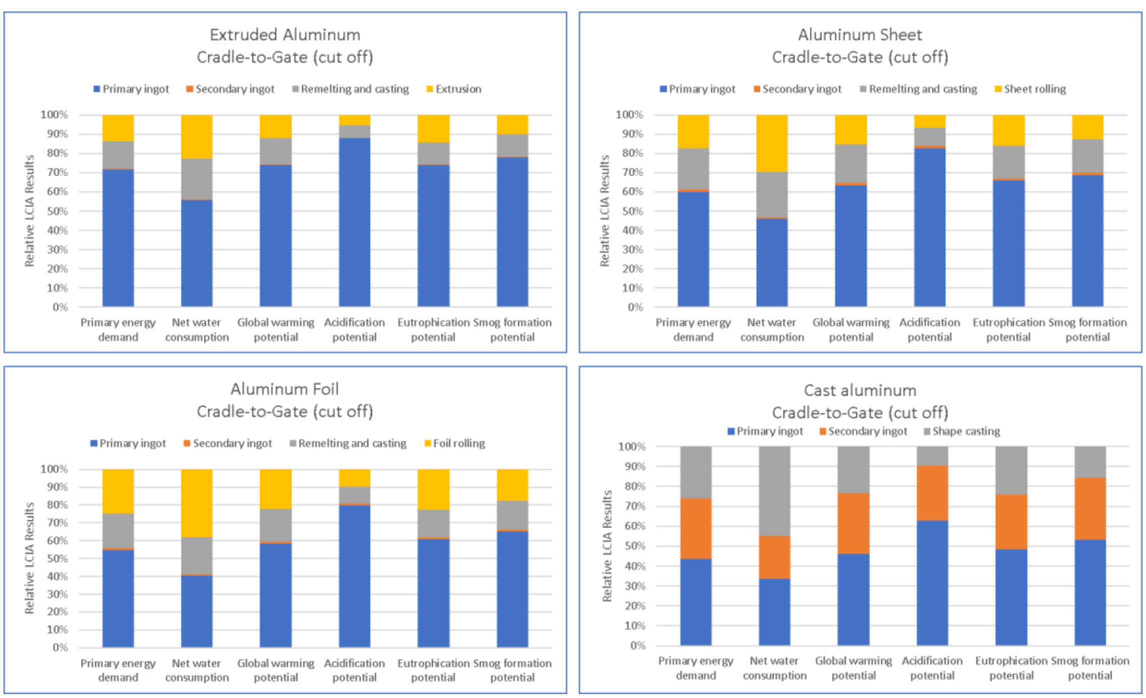

Figure 9-1: Breakdown of Cradle-to-Gate LCIA Results for extrusion, sheet, foil and cast aluminum

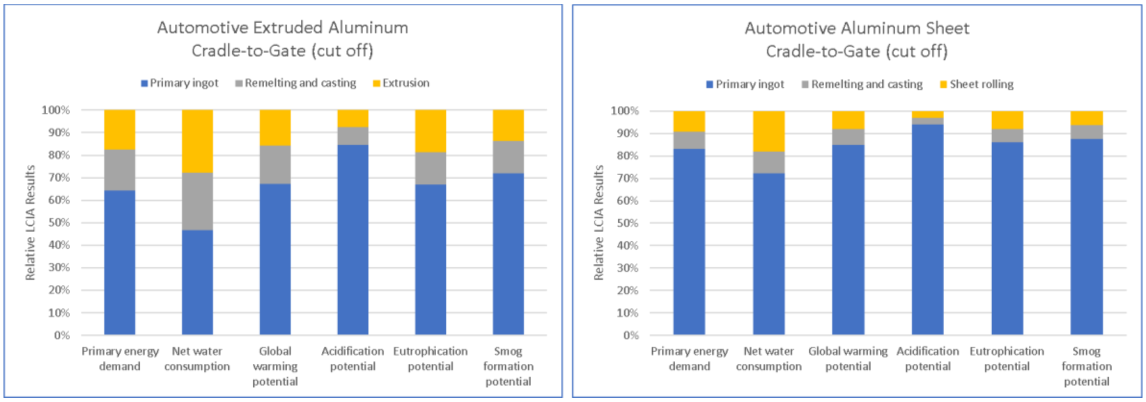

Figure 9-2: Breakdown of Cradle-to-Gate LCIA Results for automotive extrusion and sheet

9.1.2 Recycled Metal Reduces Footprint

Given the significant influence of primary aluminum on the cradle-to-gate footprint, one way to address it is to reduce the use of primary aluminum and increase the use of recycled metal. A ***sensitivity analysis*** was conducted to examine the effect of increasing primary aluminum content in the products. As shown in **Figure 9-3** and **Figure 9-4**, a one percent increase in primary aluminum content in the products will increase the cradle-to-gate primary energy demand and global warming potential by as much as **1856 MJ** and **117 kg CO2e**, respectively, for 1,000 kg semi-finished products. **This is equal to say that a one percentage point increase in recycled aluminum content will reduce the energy demand and carbon footprint by the same amount.**

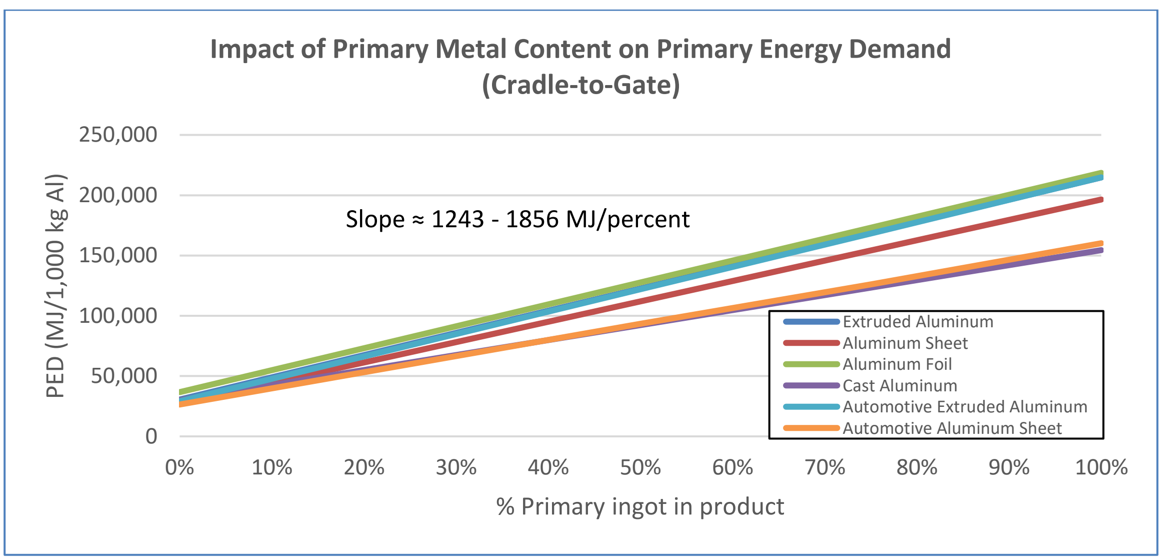

Figure 9-3: The impact of primary and recycled metal use on cradle-to-gate energy demand of semi-fab aluminum products

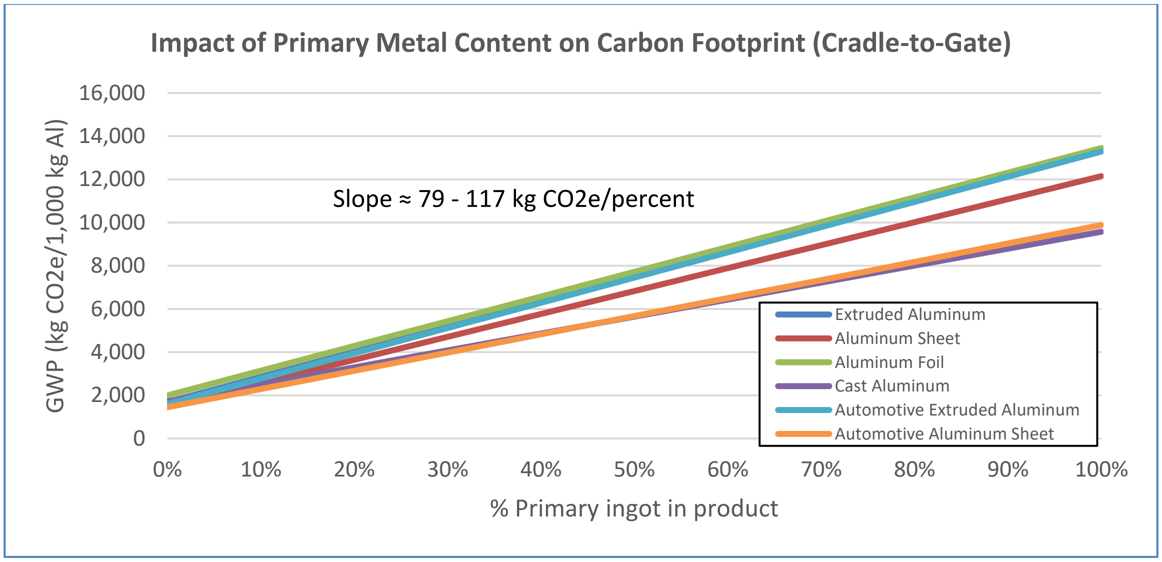

Figure 9-4: The impact of primary and recycled metal use on cradle-to-gate carbon footprint of semi-fab aluminum products

The effect of increasing primary aluminum content in the products can be seen in **Table 9-1** for each of the product groups and LCIA indicators examined. This is equal to say that each percentage reduction in primary aluminum and increase in recycled aluminum will reduce the footprint by the indicated amount. **This information can be used to calculate the results of specific products made by a specific manufacturer of which the products have different metal compositions than the weighted averages of the industry**.

Table 9-1: Impact of increasing primary aluminum content by one percentage point on the cradle-to-gate LCIA results (slopes of the sensitivity analysis lines), representing 1,000 kg of products

Assessment Parameter	Extrusion	Sheet	Foil	Die Cast	Automotive Extrusion	Automotive Sheet
Primary energy demand (MJ)	1842.00	1688.95	1818.56	1243.45	1856.46	1337.15
Global warming potential (kg CO2e)	116.02	106.39	114.55	78.54	116.92	84.37
Acidification potential (kg SO2e)	0.53	0.49	0.53	0.37	0.54	0.39
Eutrophication potential (kg Ne)	0.01	0.01	0.01	0.01	0.01	0.01
Smog formation potential (kg O3e)	4.47	4.10	4.42	3.06	4.51	3.26

Meanwhile, we have to recognize that the ability for manufacturers to increase the use of recycled aluminum is constrained by both resource availability and certain technical hurdles. Aluminum scrap as a resource is limited by its availability since most scrap is from post-consumer products. Most aluminum products have a very long lifetime in use, particularly those in buildings, infrastructure facilities, transportation equipment and vehicles, and durable goods. Scrap can only be made available when a product is taken out of service and gets collected and recycled.

In addition to availability, scrap is often "contaminated" when it is collected and recycled in a mixed material and mixed alloy environment. For aluminum scrap to be effectively used to make a new product, the contamination must be removed by sorting, segregation and cleaning. Current infrastructure in the recycling system is not good enough to efficiently and effectively segregate different materials and sort different alloys. These technical hurdles need to be solved to achieve a true closed-loop recycling system for aluminum and other metal materials.

9.1.3 Not All Primary Aluminum Is Created Equal

Another way to achieve environmental impact reduction for manufacturers is to source cleaner primary aluminum. To see the effect of primary aluminum sourcing, a ***scenario analysis*** was conducted to alternate the sourcing from different regions or countries other than the baseline case of the North American consumption mix. The metal compositions – shares of primary and recycled metal in the products, are kept unchanged for the scenario analysis. **Figure 9-5** and **Figure 9-6** show the effects of primary aluminum sourcing on cradle-to-gate primary energy demand and global warming potential, respectively. The regions and countries included in the scenario analysis are:

- RNA represents the weighted average of primary aluminum consumption mix in North America, which is the baseline case;
- CA represents Canada where primary aluminum is exclusively smelted with hydropower electricity;
- CN represents China where primary aluminum is mainly smelted with coal-fired electricity;
- RME represents the Middle East where primary aluminum is mainly smelted with natural gas fired electricity.

Clearly, the scale of difference is dependent both on impact category (e.g., PED or GWP) and on how much primary aluminum content is in the products. The more primary aluminum is in the product, the more striking the difference between hydropower smelted aluminum and coal-power smelted aluminum. The difference is more prominent for GWP than it is for PED. The cradle-to-gate carbon footprint of automotive aluminum sheet made of Chinese primary aluminum would be 3.2 times higher than it is made of Canadian primary aluminum under the same share of primary and recycled content as the baseline case.

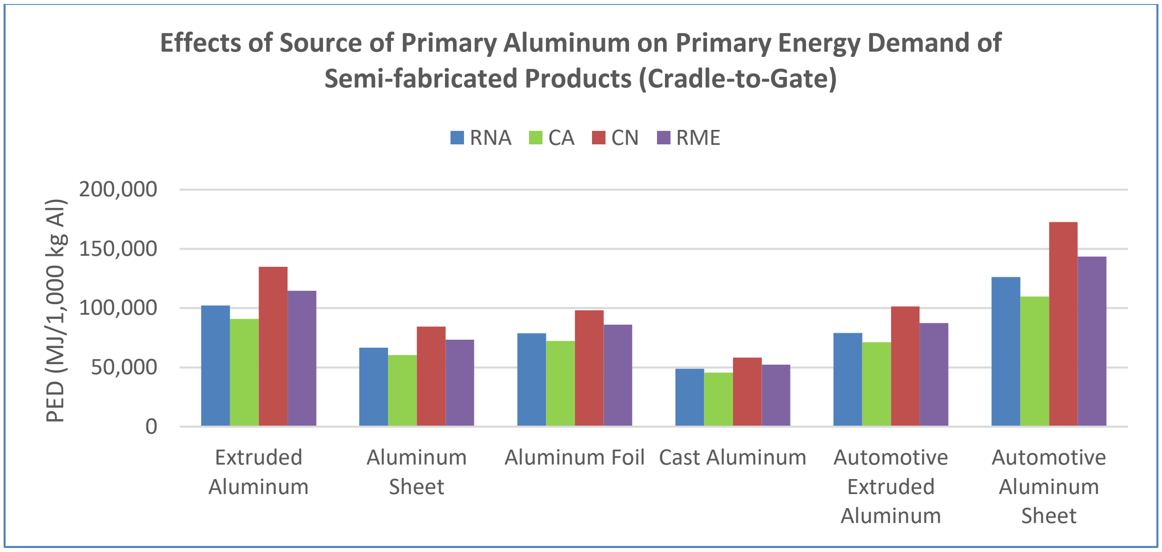

Figure 9-5: Effect of source of primary aluminum on Cradle-to-Gate primary energy demand. RNA: North America; CA: Canada; CN: China; RME: Middle East.

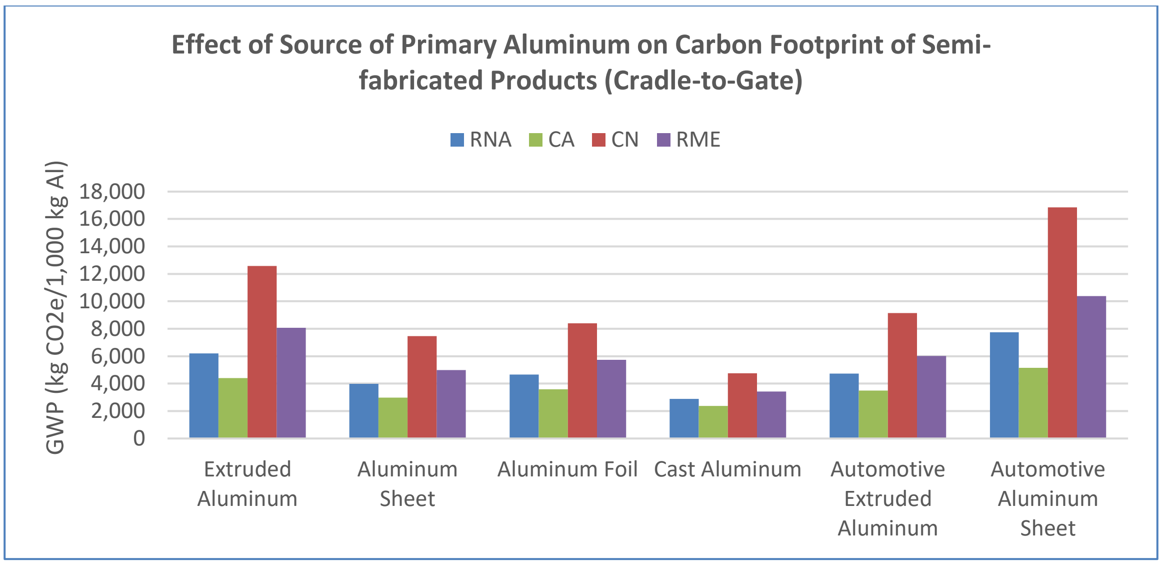

Figure 9-6: Effect of source of primary aluminum on Cradle-to-Gate carbon footprint. RNA: North America; CA: Canada; CN: China; RME: Middle East.

9.2 Cradle-to-Grave

9.2.1 EOL Recycling Helps Significantly Reduce Footprints

From a ***cradle-to-grave*** perspective, the recycling of aluminum at the end of its useful life can significantly reduce the environmental footprint and therefore the potential environmental impacts (**Figure 9-7** and **Figure 9-8**, showing in light blow color as the net recycling credits). A detailed breakdown of the results by manufacturing processes for each product system is listed in the **Appendix** (**0**).

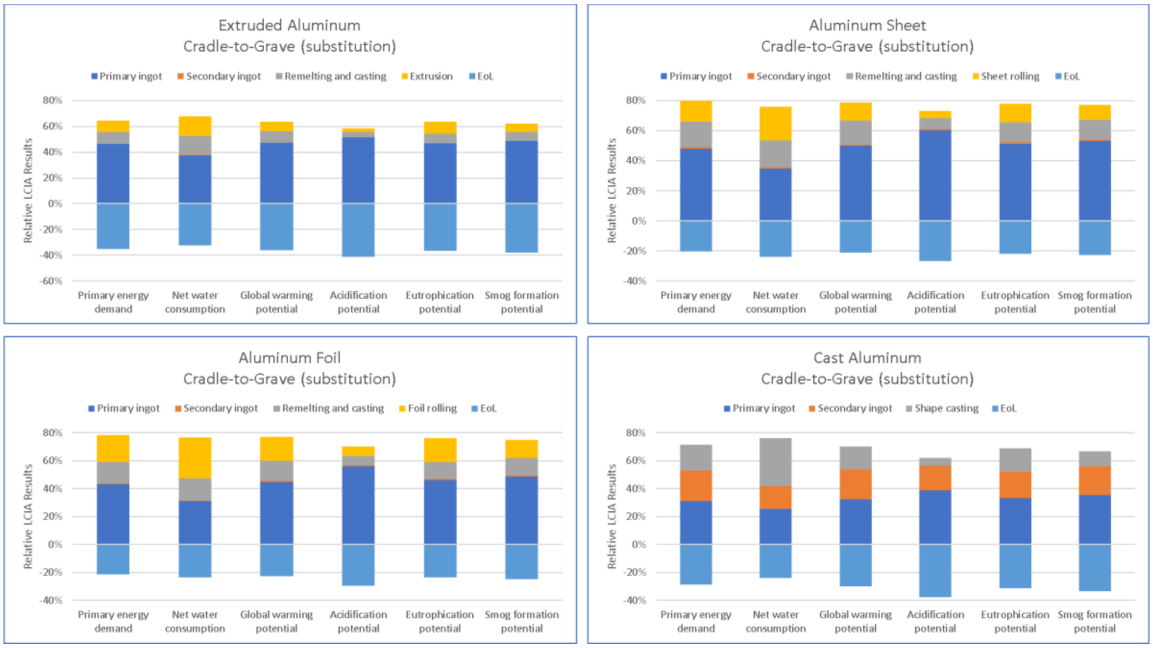

Figure 9-7: Breakdown of Cradle-to-Grave (excluding fabrication and use phases) LCIA results

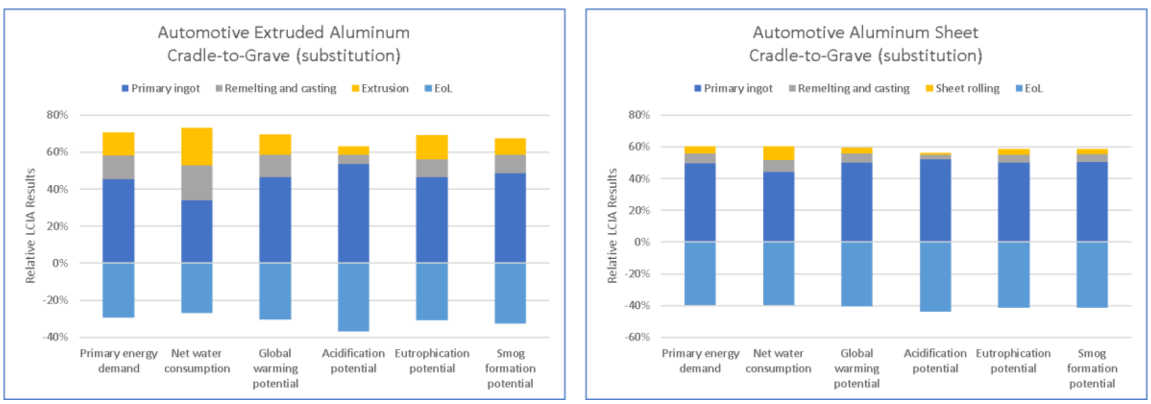

Figure 9-8: Breakdown of Cradle-to-Grave (excluding fabrication and use phases) LCIA results

To further examine the impact of recycling, another ***sensitivity analysis*** was conducted by varying the EOL recycling rates from 0 to 100 percent. The effect of increasing EOL recycling rates can be seen from both **Figure 9-9** and **Figure 9-10**. The figures show that **each percentage increase in EOL recycling can reduce the overall energy demand and global warming potential by *1,266 MJ* and *80 kg CO2e*, respectively for 1,000 kg products** for all examined product systems. Similar effects can also be observed regarding to other impact indicators. **Table 9-2 provides a handy tool for users to calculate the cradle-to-grave footprint of similar products when assuming different EOL recycling rates**.

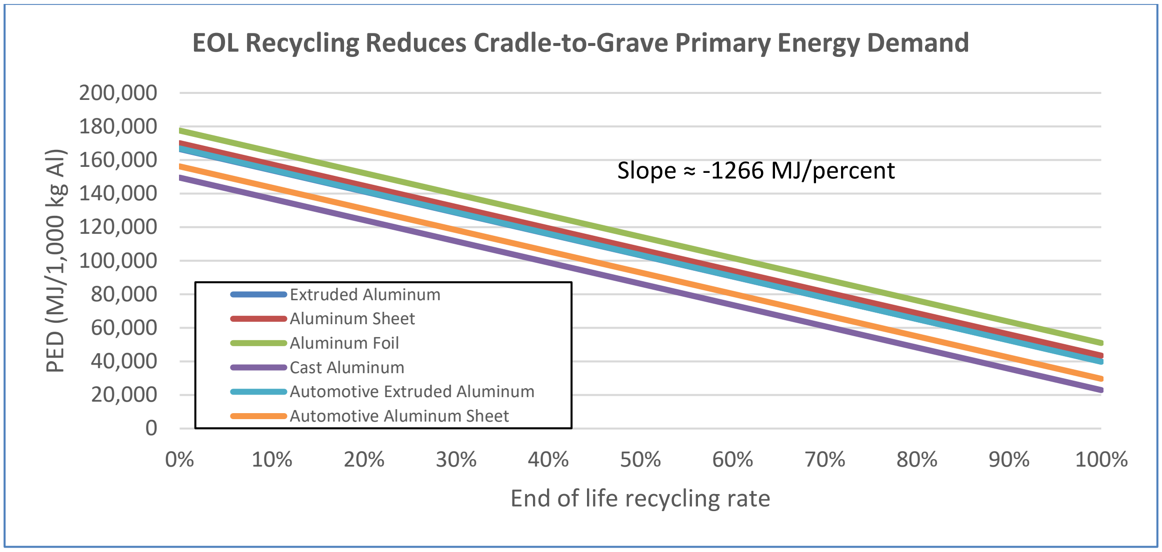

Figure 9-9: The impact of recycling on the overall primary energy demand of semi-fabricated aluminum products

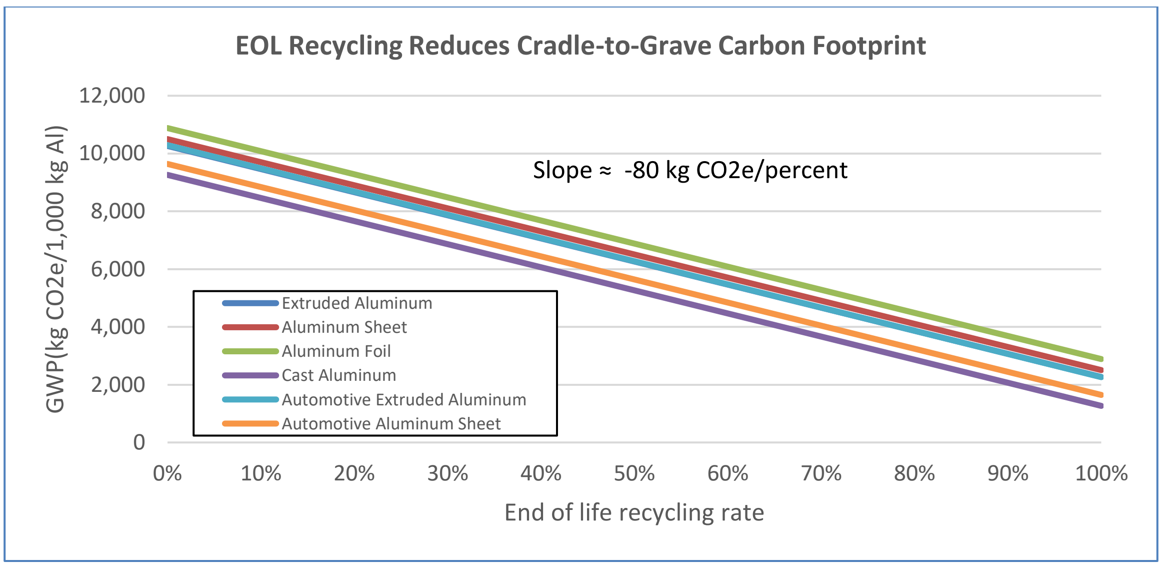

Figure 9-10: The impact of recycling on the overall global warming potential of semi-fabricated aluminum products

Table 9-2: Impact of increasing EOL recycling by one percentage point on the cradle-to-grave LCIA results (slopes of the sensitivity analysis lines), representing 1,000 kg of products

Assessment Parameter	**Extrusion**	**Sheet**	**Foil**	**Die Cast**	**Automotive Extrusion**	**Automotive Sheet**
Primary energy demand (MJ)	-1265.88	-1265.88	-1265.88	-1265.88	-1271.54	-1265.88
Global warming potential(kg CO_2e)	-79.93	-79.93	-79.93	-79.93	-80.29	-79.93

Acidification potential (kg SO2e)	-0.38	-0.38	-0.38	-0.38	-0.38	-0.38
Eutrophication potential (kg Ne)	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
Smog formation potential (kg O3e)	-3.13	-3.13	-3.13	-3.13	-3.14	-3.13

The generic environmental benefit of recycling can be quantitatively calculated by comparing the cradle-to-gate primary energy demand and carbon footprint associated with primary metal production and recycled metal production. **Figure 9-11** and **Figure 9-12** show the result of such comparison. **Clearly, recycling aluminum saves *93 percent* of energy and reduces *94 percent* of GHG emissions comparing to producing the metal from bauxite ore.**

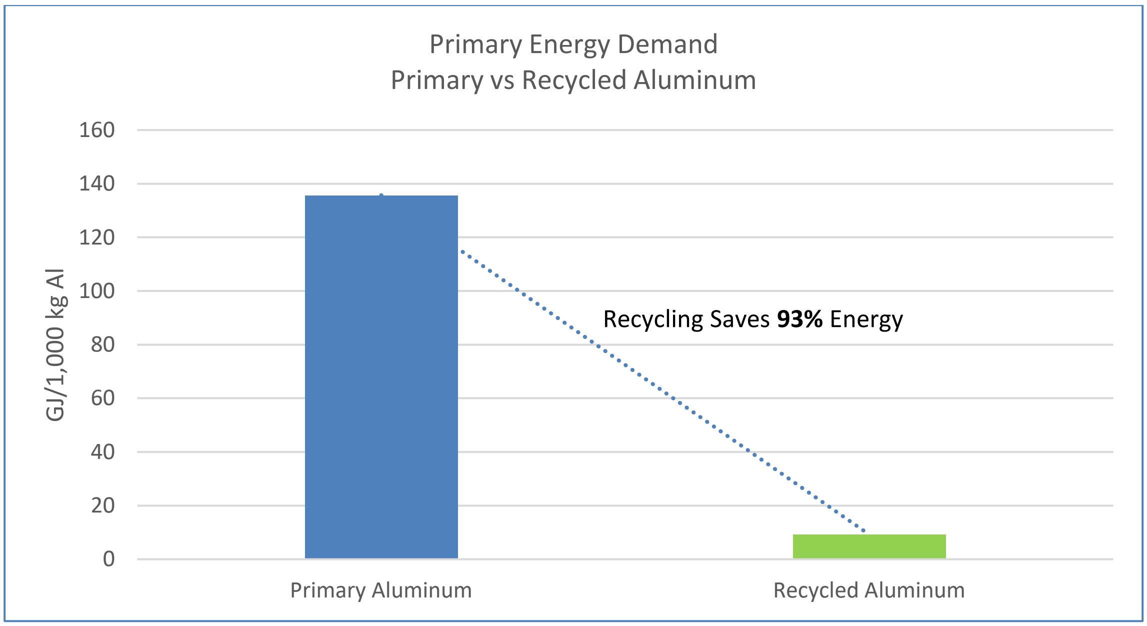

Figure 9-11: Energy savings of aluminum recycling

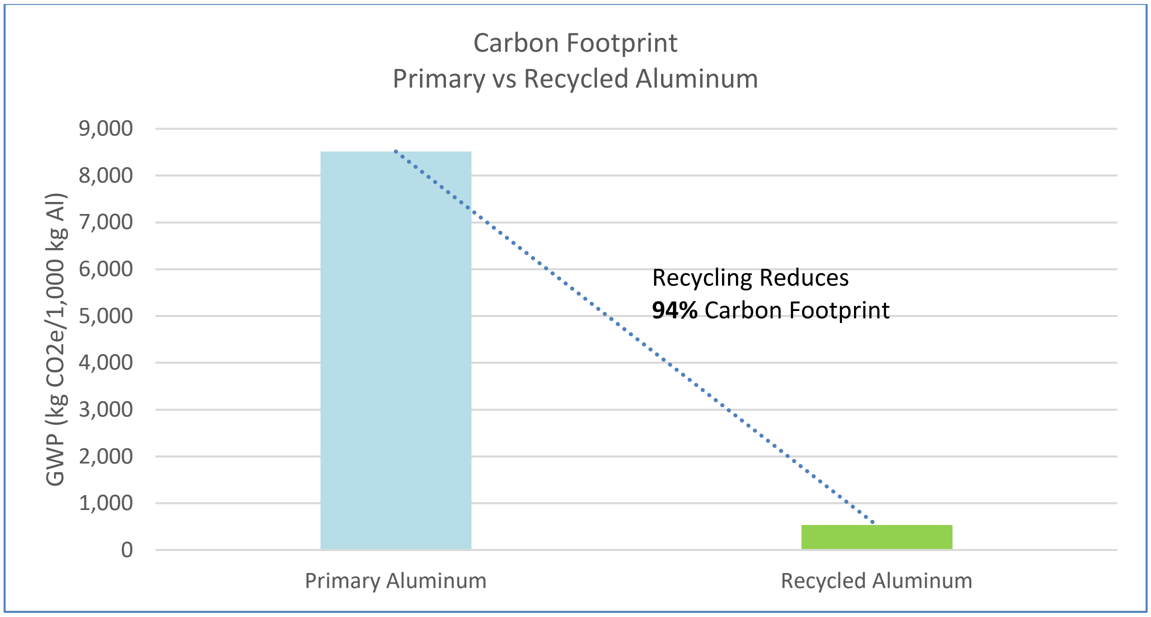

Figure 9-12: Carbon footprint reduction associated with aluminum recycling

9.3 Significant Footprint Reductions Achieved

Progress can be measured by benchmarking with historical studies. During the past three decades, the Aluminum Association has sponsored numerous LCA studies. Many of them were either concentrated on assessing a particular product (1993, 2010 and 2014 studies) or product shipped to a particular market sector (1998 study), while others were focused on assessing generic semi-fabricated aluminum (2013 study). While the goal and scope of these studies have been somewhat different, it is still possible to extract information to document progress. For instance, all studies have covered primary aluminum and aluminum recycling. This enables comparisons to identify trends for raw material production. In addition, the 2013 study is similar in scope and thus enables comparisons of generic semi-fabricated products.

From ***a cradle-to-gate perspective***, significant progress has been made in the aluminum industry in improving energy efficiency and reducing emissions:

- For primary aluminum, energy demand and carbon footprint have been reduced **27 percent** and **49 percent** since 1991, respectively (**Figure 9-13**);
- For recycled aluminum, energy demand and carbon footprint have been reduced **49 percent** and **60 percent** since 1991, respectively (**Figure 9-14**)
- For generic semi-fabricated products, a similar downward trend can be seen regarding to energy demand and carbon footprint since 2010 (**Figure 9-15**)

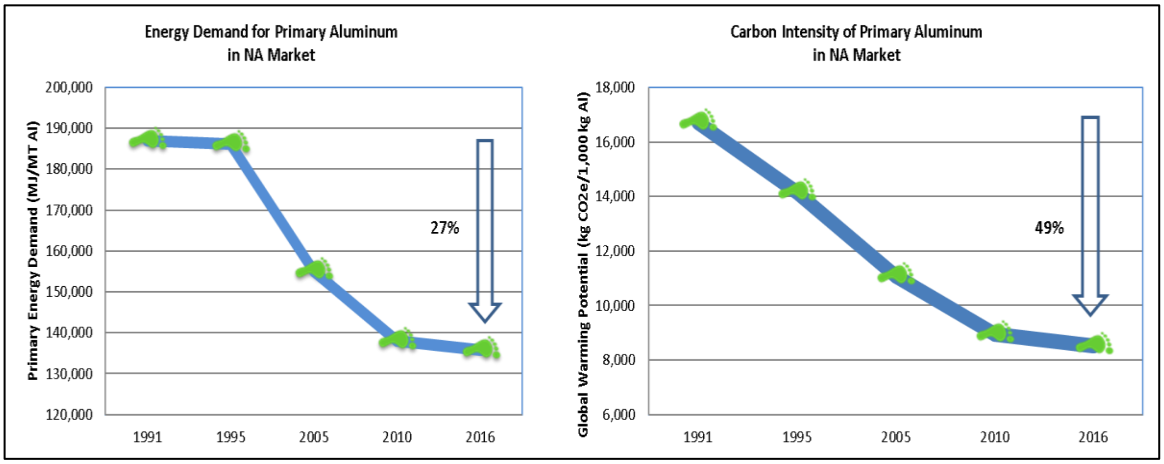

Figure 9-13: Trend of primary energy demand and carbon footprint associated with primary aluminum production.

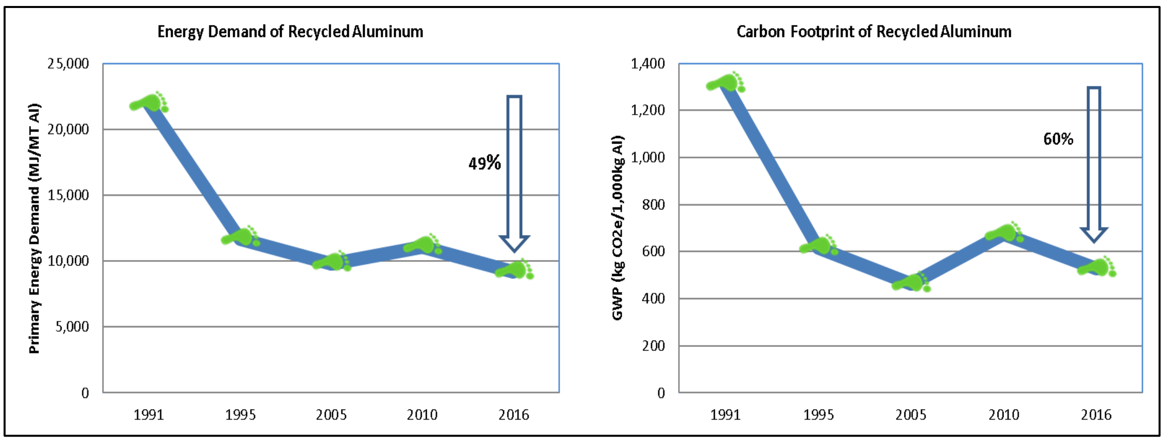

Figure 9-14: Trend of primary energy demand and carbon footprint associated with recycled aluminum

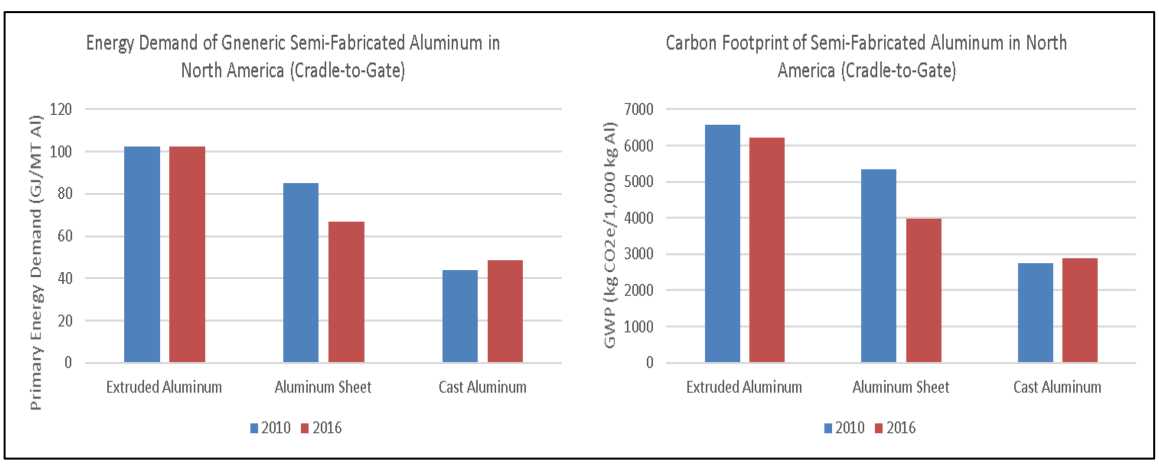

Figure 9-15: Trend of primary energy demand associated with generic semi-fabricated aluminum (cradle-to-gate)

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While the complexity of the product systems in benchmarking reminds us to not jump into easy conclusions, it is nevertheless worth to point out several key factors that lead to the improvements.

For ***primary aluminum***, the improvement in energy efficiency and carbon footprint is partly attributed to technological progress in which computerized process controls have enabled less electric power consumption during the electrolysis process and reduced greenhouse gas emissions such as CO_2 and PFCs (**Figure 9-16** and **Figure 9-17**).

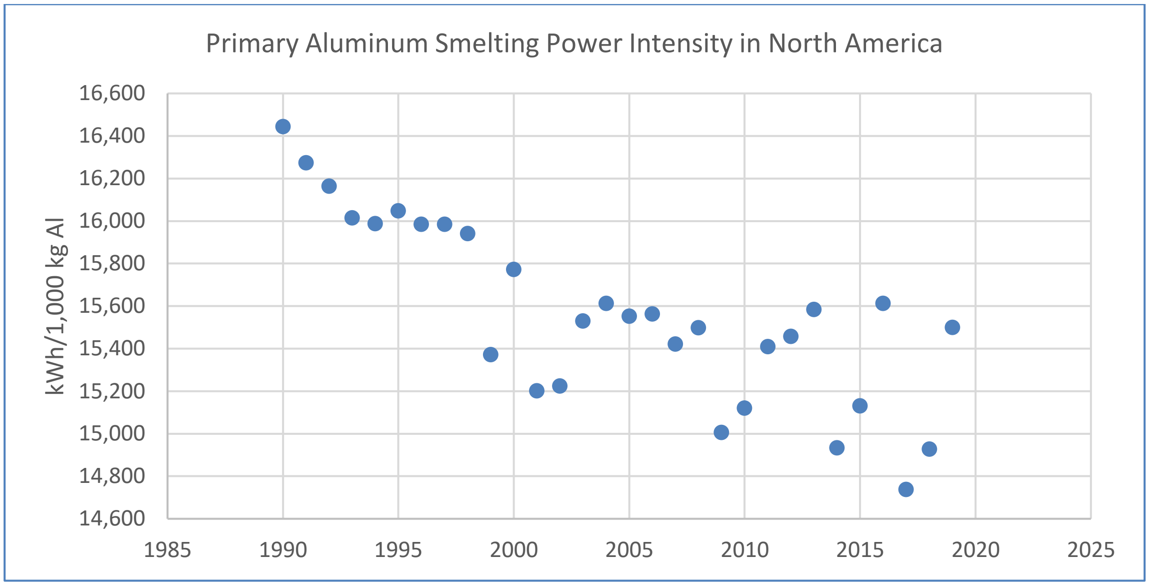

Figure 9-16: Trend of electric power consumption of primary aluminum smelting.

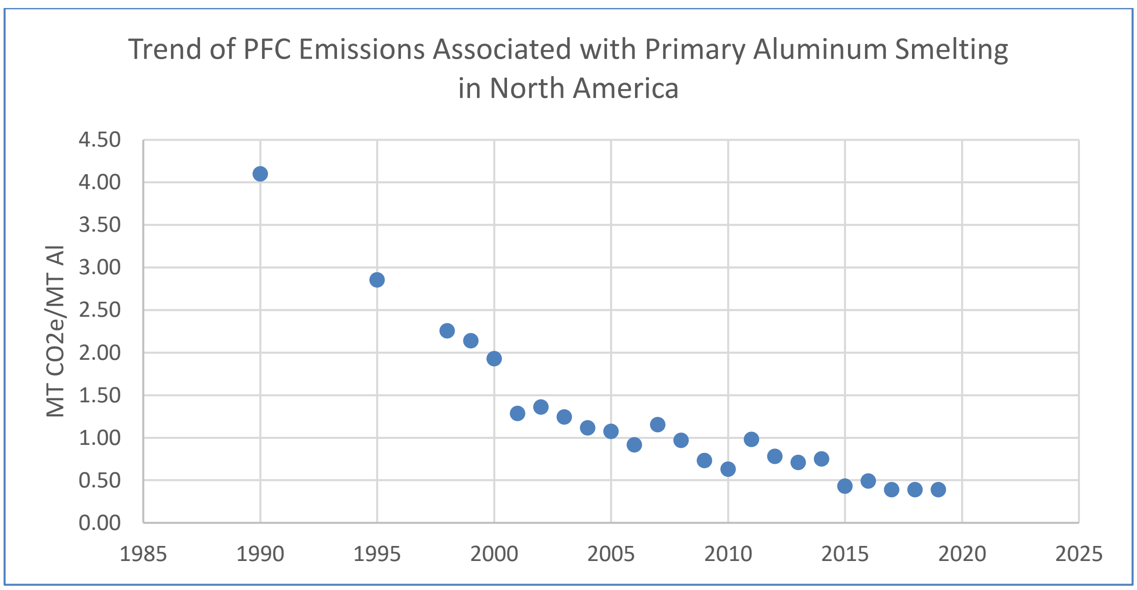

Figure 9-17: PFC emission intensity reductions

The improvement for primary aluminum 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 30 years, Söderberg facilities have been gradually closed and more pre-bake facilities have been built.

A third factor for the improvement of primary aluminum is attributed to the gradually increased share of renewable electricity and decreased share of coal fired electricity as an energy feedstock for primary aluminum smelting (**Figure 9-18**). This phenomenon is related in part to the phase out of Söderberg facilities which tend 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 and other renewable electricity.

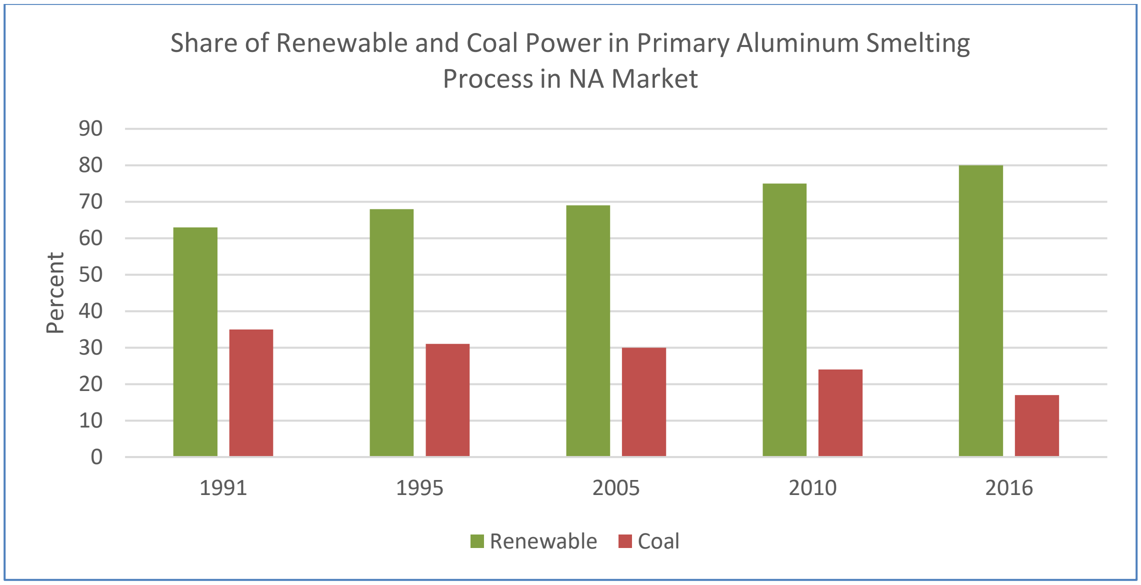

Figure 9-18: Relative shares of renewable (hydro and other renewable) and coal fired power for primary aluminum smelting in North America.

For ***recycled aluminum***, progress over the years can be mostly attributed to process efficiency improvement. Furnaces are more efficient today than 30 years ago. In addition, several other factors are likely contributing to the reductions in energy and carbon footprint as well. These include economies of scale (today's recycling facilities are larger than 30 years ago), scrap feedstock quality improvement (e.g., better sorting and better pre-treatment of scrap), variation in product forms for delivery (e.g., molten metal versus ingots), among others.

Improvement for ***semi-fabricated products*** is more complex since the cradle-to-gate footprint is not only related to production efficiency of the semi-fabrication processes themselves, but also to the footprint of primary and recycled metal, as well as the relative shares of primary versus recycled content. For instance, both extrusion and sheet products have seen an improvement in energy demand and carbon footprint. This is attributed to two major factors:

- improvement in the footprint of raw materials, and
- increase of recycled metal content (or decrease of primary metal content)

On the other hand, cast products have experienced an increase in footprint. This is largely attributed to differences in production technologies assessed between the 2010 and 2016 productions. The ultimate cause for the increase is due to the recycled metal content:

- In the 2013 study (production year 2010), cast product was represented by **sand casting** technology and average recycled metal content was ***85 percent***;

- In this study, however, the production is represented by **die casting** technology and average recycled metal content is assumed to be ***80 percent***.

9.4 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 cautioned against drawing 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 transportation, packaging, building & construction, and consumer durables. For example, the production phase of an automobile is as little as 10 percent of the total life cycle footprint while the rest is due to the energy consumptions during the use phase (Hottle, et al, 2017). Therefore, focusing solely on the production phase of a product like an automobile will lead to incomplete environmental impact assessment and create unintended consequences.

Comparing to the production phase, the use phase is usually product specific and is not as straightforward. LCA practitioners should 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. **This study can be used as the foundation for data users to build their use phase upon it**.

9.5 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 beneficial use of aluminum and through improved quality of EOL recycling**.

As stated previously, the use of aluminum could substantially improve the overall environmental footprint of a product:

- Aluminum as a strong and lightweight automotive material can significantly reduce the energy consumption of the vehicles compared to both conventional auto steel and advanced high strength steel (AHSS), and thus help reduce the overall life cycle footprint of the vehicles (Audi, 2005; Dubreuil et al, 2010; Das 2014; Bushi et al, 2015; Bushi 2018;). An EPA literature review shows that "most of the LCAs reviewed demonstrated that aluminum-intensive designs were able to achieve the largest reductions in life-cycle energy use and GHG impacts, specifically in the use phase" (Hottle, et al, 2017).
- A study by ICF International concludes that depending on retail location, GHG emissions associated with the transportation and refrigeration of beverages packaged in aluminum cans are 8-23% lower than plastic bottles and 67-90% lower than glass bottles (ICF, 2016).
- Studies by the European Aluminum Foil Association conclude that aluminum foil used for food and beverage packaging plays a key role in "minimizing the overall

environmental impact of the product by reducing spoilage, over consumption, and/or by facilitating more sustainable lifestyles" (EAFA, 2008, 2009, 2010, 2011, 2013).

- Aluminum helps improve energy efficiency of a building. Strong, lightweight and durable aluminum products contribute to controlled and optimized functioning of heating, cooling, lighting, and ventilation systems. The optimization is achieved through balancing the competing needs of occupants in terms of optimal indoor temperature, maximum daylight and view, and maximum fresh air (AA Green Building Guide 2015).

Aluminum is a perfect material for recycling. When properly collected, sorted, and segregated, the recycling process does not change any functionality of the metal, regardless of how many times it is recycled. While aluminum products for transportation, infrastructure, building and construction, and durable goods have been historically mostly recycled at the end of life, the recycling rates for some consumer products such as packaging are far from expectation. It is estimated that a significant amount of aluminum, more than a million tons, is lost in landfills each year in the North American region. The recycling of these lost metals will not only help the industry reduce its environmental footprints, but also help society save the metals and the attached energy resources for future generations, thus achieving the ultimate goal of sustainable development for humanity.

Even for products with high recycling rates, the potential for improvement is still significant. The current recycling infrastructure available and technology deployed in North America does not meet the demand for increasing the quality of recycling and closed-loop recycling of aluminum. Aluminum scrap collected is often mixed with other materials, and most harmfully, mixed with different alloys. Contamination of aluminum scrap by other materials and commingling of different aluminum alloys are common. Such contamination and commingling lead to a phenomenon called "downcycling" – where high-quality wrought aluminum alloys end up being recycled into cast alloys since cast alloys have higher tolerance for impurity. While the metal does get recycled and reused, again and again for new products, such a system is not an optimal recycling system, and it does not reuse society's scarce resources in the most efficiency way. Most importantly, it is not sustainable since the demand for cast alloy has limitations.

To address this problem, we must work together to find better solutions. Policy makers need to develop smart and effective policies to incentivize quality recycling. The scrap collection industry needs to invest in new infrastructure to meet current and future demand. And technology developers need to seize the opportunity to provide state-of-the-art technologies to improve recycling efficiency and quality. The Aluminum Association calls on all stakeholders to work together to improve our aging recycling system to meet the 21st century demand for optimal use of our planet's scarce resources.

10. Critical Review Comments and Answers

10.1 Internal Review Panel Comments and Answers

Table 10-1: Internal review comments and responses

Comments	Responses
Check models to ensure accuracy	A broken link between the models and the exported EXCEL spreadsheet results was identified and fixed. This affects the results of both LCI and LCIA for semi-fabricated products. Primary aluminum and recycling are not affected.
Executive summary too long	The executive summary is shortened. Some illustration figures have been grouped together.
Terminologies and definitions	Added a Glossary for the report.
Confusion between recycling and recycled aluminum ingot	Addressed. This report avoids the term "secondary aluminum" as much as possible since it's not a standard term used by the aluminum industry (refer to Global Advisory Group GAG Guidance 3rd Edition 2011-01). The term "recycled/secondary aluminum ingot" is replaced with the industry common term "remelt secondary ingot (RSI)".
Sensitivity analysis: the relationship between LCIA results and primary aluminum content or EOL recycling rate	Addressed. The relationship between the change in absolute values of LCIA results and the per percentage change of primary aluminum content or EOL recycling rate, e.g., value/percent, is linear. However, the relationship between the percentage change in LCIA results and the per percentage change of primary aluminum content or EOL recycling rate, e.g., percent/percent, is not linear since it depends on the specific values of the baseline primary aluminum content or recycling rate. Slope values for all impact assessment parameters are now included in Table 9.1 and 9.2 for each semi-fabricated product systems.
Possible confusion between CO2 emission results in Chapter 7 and GWP results in Chapter 8	Addressed with special notes in the text, tables, and figures. CO2 emissions in Chapter 7 are the results of inventory analysis and it refers to CO2 emissions only, excluding other GHG emissions. The results in Chapter 8, on the other hand, are potential global warming impacts of all GHG emissions including CO2 and others.
Adding breakdown information by manufacturing processes for each of the semi-fabricated product systems	Added, both Cradle-to-Gate and Cradle-to-Grave, in Appendix 12.3.
Illustration of how the models	Addressed.

were built and results calculated using automotive sheet as an example	

10.2 External Review Comments and Answers

10.2.1 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-Fabricated Aluminum Products in North America: A Life-Cycle Assessment Report*. The following is a summary of the review results of the *Draft Report*, September 2021.

10.2.2 Reviewer

Stephanie Carlisle	University of Washington
Yuan Yao	Yale University

10.2.3 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 the overall appropriateness for the report to be served as a background document to support potential near-future environmental product declarations (EPDs) and carbon footprint declarations (CFs) of aluminum products including:

- Primary Aluminum Ingot
- Remelt Secondary Aluminum Ingot (RSI)
- Flat-rolled Products
- Extruded Products
- Die Cast Products

10.2.4 Review Comments and Answers

Line number this version	Line number previous	Comments	Response

	version		
446-447	499-500	LCA Definition	Addressed
449-450	503-504	Scope of the study versus “cradle-to-gate” and “cradle-to-grave”	Addressed
454	507	Detailed system boundary statement	This part of the report is just an ES in which I’m trying to keep it shorter. Details of system boundaries are elaborated in relevant chapters.
469-471	524-526	Use of terminology	Addressed
472-474	529-530	Transparency	Addressed
497-498	559	Wondering whether the weights of different products are disclosed? This seems to be the essential information for the results. It would be nice to see the weight data and the results of each individual products.	Weighting methods are discussed in relevant chapters. However, the weighted average of the actual mix of primary and recycled metal input for each product groups is calculated by using the production output of each reporting facility as weighting factor. Such information is sensitive business information for companies, and it is not disclosed. The association is legally responsible for protecting confidential business information of manufacturing companies.
507 (Table 0-1)	570	Selection of impact categories	The selection of impact categories in this report is consistent with the previous reports published by AA. The primary goal is consistency. In addition, we are aware of the ongoing debate on some of the categories such as ecosystem toxicity potential and human toxicity potential. The aluminum industry is cautious in adopting these categories before the scientific debate is settled.
510 (Table 0-2)	573	Why primary ingot is all zero	This is a recycling dataset, reflecting using 100 aluminum percent of scrap as feedstock. No primary aluminum is added.
521-528	587-593	Energy – electricity – primary aluminum	Supporting information is in related chapters. As for the ES, this is simply direct statement informing the findings.
531 (Figure 0-1)	599	Why cut off is shown on the top of each figure? what materials flows were cut off in	“Cut off” indicates how cradle-to-gate footprint is calculated. It does not mean that there are any flows

		the LCA? Unclear to me	been cut off. Allocation method and cut-off criteria both use the same term but they are different things.
539-541	611-613	Range of slope in lines	Addressed
544 (Figure 0-3)	618	Share of primary and recycled aluminum in products	Refer to Section 7.3.1.2.
544 (Figure 0-3)	618	Why only carbon footprint is included in the ES?	Carbon footprint is certainly in the spotlight of public attention. Energy is also the attention of the public. Given the limited space in ES, we decided to only use carbon footprint as an example. Other impact categories are elaborated in Chapter 7 and 8.
555-557	631-633	Is scrap processing (cleaning, sorting etc.) included in the study?	Yes, please refer to Chapter 7.
567-574	645-652	Is the power mix of each country considered as part of scenario analysis?	Yes. However, the power mix of different countries and regions in the scenario analysis only refers to the power mix of primary aluminum production in that country. It is different from the average grid mix of the overall electricity consumption in that country or region.
575	653	If the scale of difference is dependent on impact categories, then all impact categories should be included in the scenario analysis.	Good point. However, we only focused on energy and carbon in the scenario analysis. The goal is to provided users a snapshot. Given the balky size of this report, users are encouraged to conduct their own analysis for other impact categories. Because the major source of environmental impact of aluminum products is energy related, the scale difference for other categories will not be far from the scale of PED.
599-601	684-686	Allocation for recycled aluminum	For allocation approaches, please refer to Chapter 5.
631 (Figure 0-9)	725	Why an increase for casting products?	See line 664-671 for explanation.
639 (Figure 0-10)	734	The fluctuation of power intensity for primary aluminum smelting	This is largely attributed to the share of output from old and inefficient smelters since the intensity is a weighted average based on the output of each of the

			smelters. When the production of old smelters is curtailed, power intensity goes down. Otherwise, it goes up.
646-647	744-745	Is the statement for NA or global?	NA. This report is all about the NA market.
654 (Figure 0-12)	754	Data source	IAI and AA. Calculated based on primary data collected from smelters.
664-671	766-773	Share of primary versus recycled metal in products	Refer to Chapter 7.
705-726	812-833	Cited use phase studies	Yes, some of them are full lifecycle studies including the use phase. Others are only use phase analysis.
727-729	835-837	Aluminum a perfect material for recycling? What about contamination?	Yes, theoretically, all common metal materials are perfectly recyclable and regardless of how many times they are recycled, the properties remain the same. This is because metals are composed of atoms – the smallest particles that do not change by conventional thermal and mechanical forces. In the real-world practice, however, it is always possible that different alloys and materials end up mixing together. But this is an operational issue. People can choose to carefully recycle different alloys separately, or they can rely on technology to sort and segregate different materials and alloys so that closed-loop recycling can be achieved.
732-733	840-841	Any reference to support the claim of more than a million tons of aluminum lost each year?	Unfortunately, no. Tracking material loss in real life is a touch job for any materials. The lifetime of most aluminum products is in the scale of decades of years. A million ton of loss is based on our estimates of loss for packaging materials.
754	864	Another important area is product design – design for recycling.	Fully agree.
924-928	1058-1062	About comparative LCA	This is not about good comparative studies. It refers to bad PR practice in which the carbon footprint of a kilogram of

			one material is compared with another material without a product and its functionality in mind. Material by itself has no meaning if it is not used to make products. When a product of the same function is made of different materials, the quantity of each material used is different. Thus, comparing the environmental footprint of materials on a per unit weight basis is meaningless and it is completely misleading.
945	1081	Which beverage can LCA is it refer to?	Addressed
987	1138	Disclosure of weighting factors by production facilities	Unfortunately, no. We are legally prohibited to disclose such information. The information is considered proprietary business information.
1026-1027	1187-1188	Reference to commercial database	Addressed
1078-1081	1256-1259	Data coverage calculation by other industries	Addressed
1100-1107	1285-1291	Use of secondary data from database	Addressed but not separately listed since there are many of them. As stated, relevant data in the GaBi database was used. These include production and processing of auxiliary materials, production of fuels, generation, transmission and distribution of electricity, transportation, waste treatment and disposal, among others.
1146 and 1153 (Figure 4-2 and 4-3)	1338 and 1347	Vertical and horizontal weighting method	Weighting is based on the share of output of each facility in a production process in which an intermediate or final product is produced. Large facility has higher weight and small facility has lower weight.
1294-1295	1496-1497	Inputs and outputs versus environmental impacts	Addressed.
1297-1298	1498-1500	Shouldn't the reason of allocation be the co-existence of closed loop and open loop recycling in the industry?	Allocation is to divide inputs and outputs between the product system that generates scrap and the product system that utilizes scrap. Both closed loop and open loop productions involve

			allocation.
1302-1305	1506-1509	Use of new and old scrap having the same chemical properties as justification for taking a unified approach of allocation for both	Indeed, new and old scrap have the same chemical properties since they were originated from the same piece of metal. The only difference is timing for them to be available to be recycled. In the real-world markets, old scrap could be mixed with different alloys and materials and thus getting "contaminated". So do new scrap. The chance of getting contaminated is not much of a difference for both in the real-world scrap market practice. What was referred to as "no significant treatment required" in the "Glossary" section for scrap definition was strictly refer to "internal" or "run-around" scrap.
1332	1539	Net-scrap approach	Addressed
1418	1615-1616	Complete transparency approach	Addressed
1424-1426	1621-1623	Assumptions (for splitting mixed scrap reported by producers)	The assumptions are made case by case based on following up with reporters to get a better understanding of the main characteristics of those mixed scrap. No one-size-fits-all assumption was used.
1467-1468	1676	IPCC characterization factors	IPCC AR5. This usually depends on which version is in the most current GaBi software. The software is constantly updating.
1557-1558	1781-1782	How were the recycling difficulties and compromised quality of Al scrap considered in the net scrap approach discussed in the previous section?	This study does not factor "downcycling" of aluminum in its recycling allocation approach. This is because the study is a generic aluminum product assessment without focusing on a specific product and its use. The aluminum downcycling does happen in real-world recycling practice. However, it depends on specific products and market sectors. Even within a specific product group or market sector, it is still case by case in nature. Without a specific case, we can not make reasonable

			assumptions to discount for downcycling.
1578-1580	1805-1806	Scrap processing: were these processes included in the LCA?	Yes. It's included in the recycling dataset and subsequently included in all semi-fabricated products.
1616 (Table 6-2)	1848	Were AA and IAI represent the LCI collected as primary data?	Yes. All input and output data for primary aluminum production processes are directly collected by IAI and assisted by AA in case of North America, from production facilities.
1639	1875	Official data source	Official data source refers to data from government agencies or trade associations
1798	2078	Source of anodes	We have no statistical data to show the shares of domestic production and imports, nor do we have data to show where it is imported. As stated in 7.1.1.3.2, the model uses a global average dataset for anode. Regional difference in anode production is almost negligible.
1800	2080	So how these auxiliary materials were modeled? Were they cut off?	All auxiliary materials were included. Nothing had been cut-off. The general data selection principal is domestic dataset first. If no domestic dataset is available in GaBi, a dataset from another country will be selected for the models.
1840	2129	Weighting factors for primary aluminum consumption mix for NA	This was shown in Table 6-1. Added cross reference.
1847	2138	Data source for PFC emissions	PFC emission data is primary data directly collected from smelters. The conversion factors used are stated in line 1833-1834. The year of production is 2016 as shown in Table 7-4. Note that the numbers in Table 7-4 have been modified to reflect the IPCC AR5 conversion factors used for the LCA models in this report. The numbers in the previous draft were based on IPCC AR4 conversion factors.
1903 (Table 7-6)	2211	Why only show CO2 emissions, not total GHG or say carbon footprints that	This is only a highlight of inventory in terms of energy and CO2. It is highlighted for subsequent

		include different GHGs?	inventory analysis. It is a high-level representation of analysis of most other inventory items. The inventory assessment results are listed in Chapter 8, which include total carbon footprint.
1949 (Figure 7-3)	2262	Is this for NA?	Yes. Domestic production. Figure 7-4 is consumption mix (including imports). Figure titles revised to clearly indicate their representation.
1952 (Figure 7-4)	2268	Consumption mix for NA or global?	NA. This study is all about NA. The consumption mix, as stated in the early sections, is the mixture of primary aluminum provided by "domestic" producers and countries where additional primary aluminum was imported. The total CO2 intensity is a weighted average of the consumption mix and the shares of each of the "suppliers" are depicted. Since "domestic production has an 81% share in the consumption mix, it has the highest bar in the figure.
1959	2278	Why CH4 are not discussed if it is also a major factor driving the total GWP?	Given the limited space of the report, inventory analysis can only focus on highlighting energy and CO2 emissions, which have the highest potential impact. There are literally hundreds of other items in the inventory that were neither be able to be fully listed in the report, nor can be discussed.
1972	2293	Well, this 5.07 is exactly the same with CO2 emissions from electrolysis, which indicates that electricity is only used in electrolysis process...so no electricity is used in other processes at all? This doesn't look right to me...	This is a misunderstanding of the sentence. The sentence has been modified to avoided misunderstanding. The figure shows the cradle-to-gate CO2 emissions by production process and in total. In each of the production process, there are emissions related to electricity consumption, emissions from direct fuel combustion, and in some cases emissions from chemical reaction. But those are all combined and no separate

			breakdowns. The total is the sum of all the process emissions. In the electrolysis process, the total emission is 5.07 but the figure did not show a breakdown by direct fuel combustion, the consumption of electricity, and direct release from chemical reactions. Overall, the electricity generation and transmission accounts for 70%, or 3.55 and the rest of it is largely related to chemical reaction (anode carbon react with oxygen) (this report did provide an estimated breakdown in Section 8.1.3).
2011	2342	Unclear how alloy composition was adjusted. The illustration figures also did not show any unit processes reflecting alloy composition adjustment.	Alloy composition adjustment for the production of remelt secondary ingot is not an independent process. It is simply one of the steps in RSI production. The step, as described in later pages, involves in testing of molten metal, and adding alloy agents and primary aluminum to adjust the composition into a specific chemical property required by customers.
2014 (Figure 7-7)	2346	What is cut off? Or you are referring to recycled content method - a more common name? Cut off criteria and cut off method used in the same report will be confusing to readers.	The term “cut-off approach” used in all figures of this report refers to how allocation in the models was done. It doesn’t not mean “cut-off criteria”. There were almost no “flows’ cutting off in this study, although the reported elaborated how “cut-off” would be done if there were any.
2060	2403	So only one unit process was modeled for all activities bulleted listing above? What are the data sources of LCI? Were the LCI disclosed in this report?	The reason for scrap processing/treatment to be considered and modeled as one single unit process is that’s how data is measured and reported by facilities. In theory, a factory should be able to measure and record things happening in every individual unit. However, in real-world practice, most factories are only able to measure things facility wide. Even if they were able to

			measure individual units, they would not share such data because those are the most sensitive information for a manufacturer. As a result, by treating all activities listed in scrap treatment as one unit process, it helps simply things and avoid the need for arbitrary allocation of inputs and outputs among the different activities.
2113	2468	How alloy adjustment was modeled and reflected in LCI? Were the additional elements added included in the LCI modeling?	Addressed. As stated in the previous response, alloy adjustment is just a single step of RSI production and the operation is part of the entire melting, purifying, holding and casting process. It is not an independent unit process. The raw data collected is the entire process from melting of metals to casted ingots. And, yes, alloy agents are modeled into the inventory. As stated in previous chapters, this study treats all alloy agents as primary aluminum and use primary aluminum data to substitute for alloy agents. For reasons of such treatment, refer to 4.3.5 (newly added).
2137-2138	2498-2499	Was the emission capture considered and reflected in the LCI modeling?	Yes. Data reported by the facilities is for the emissions released to the air.
2140	2503	The "unit process" has been used as in singular form throughout the section, which indicates that you only use highly aggregated LCI for a single one unit process that covers all activities mentioned here. Is that the case? If yes, how were these data collected and aggregated into one single unit process?	Refer to previous explanation for comments for line 2113.
2213	2590	How were the LCI data of these so many activities aggregated into the LCI for one single unit process? Some documentation and	Refer to previous explanation for comments for line 2113.

		clarifications are needed here.	
2248 (Table 7-8)	2633	Was the energy reported in primary energy form or direct energy consumption form?	The reported energy consumption is by fuel types and by electricity. The quantity reported is by conventional measured units. The PED, however, is in primary energy terms converted by the GaBi software using data from its database (mostly EIA data for the U.S. and IEA data for other countries). GaBi updates its database frequently to ensure the most up-to-date data is used by users.
2248 (Table 7-8)	2633	What renewable energy was included here specifically?	The renewable energy for recycled aluminum production is either from electricity (U.S. general electrical grid mix), or from primary aluminum if primary aluminum is added.
2453 (Table 7-16)	2862	Why this one doesn't distinguish old and new scrap?	As stated in the paragraph, we don't have data. The composition is assumed. We didn't try to assume the breakdown of scrap since that could be misleading.
2474	2889	Same question as below, did you model unit process for each activity listed below or these activities' LCI were aggregated into the LCI for only one unit process?	Refer to previous explanation for comments for line 2013.
2551	2987	What auxiliary materials were included in this section?	Input and output information for individual unit production processes is included in the input and output tables, which is available for users upon request. It is not included in the report due to space constraints. There are many of the input and output tables. In the case of the hot rolling process, auxiliary materials are largely various lubricant oils.
2656	3126	As mentioned earlier, no primary data were used for this process, so what local energy sources specifically were assumed here?	Except for primary aluminum production, all other production processes in this report use U.S. average grid mix for electricity. The power mix can not be traced to local levels since there are about 100 individual facilities

			involved and they are located everywhere in the U.S. and Canada.
2695 (Table 7-17)	3174	Net fresh water	Net fresh water is the difference between inflows and outflows. Most water used for aluminum production processes is cooling water. So the difference is largely caused by evaporation.
2726 (Table 8-2)	3218	The results shown in this Table are not consistent with the previous one...GWP is 8455 in the previous table, but here the total is 8515, the results for other impacts other than primary energy also have significant differences...	These are two different set of results and they should be different. One table is for NA domestic production and the other is for the NA consumption mix. The consumption mix includes not only NA domestic supply but also imports from other regions and countries. The footprint of consumption mix is slightly higher than all domestically produced primary aluminum.
2833	3354	Where this 99% is reflected?	The report has limited space to show the breakdown of each of the impact category at the individual chemical level. This statement is based on background data for inventory assessment.
2870	3399	Compared to the previously reports published or literature? baseline in what year?	As stated in line 2841, this is compared to the previous study, in which the baseline production year was 2010.
2881 (Figure 8-5)	3413	How the net scrap approach discussed in the previous section was modeled and reflected in these illustrations?	As shown in Figure 8-5 of the extrusion model, under a 95% EOL recycling rate assumption, the net scrap after satisfying the input demand of the product system in study, is 426 kg in surplus. The recycling if this surplus scrap is credited. Similar screen shots of the cradle-to-grave models are shown how other product systems are credited.
2954-2955	35087-3508	This is only the highest slope.. conclusions should not be made upon only the highest value	Addressed. See Figure 9-3.
2961 (Figure 9-4)	3515	Same comment, this is just the highest slope, should not only	Addressed. See Figure 9-4.

		list the highest slope and make a conclusion based on only part of the data points.	
1109	1294	Will the specific database entries and flows be listed in an appendix? It would be helpful to be transparent about this model inputs in terms of Date, database version and source for researchers seeking to replicate these models outside of GaBi. At what resolution can this data/model structure be shared? Per process? Sources of grid mix and power?	This comment is partially answered when addressing relevant comments from the previous reviewer. We understand that more transparency at this front will be helpful for users. However, the report itself is constrained by space. We recognize that a 140-page report for a LCA report by a trade association is already unusual and more of such disclosures on very specific details will certainly make the report much bulkier. The second consideration is the background secondary data is all from the GaBi database and AA has very limited freedom on how the data should be presented. The last consideration is the GaBi database is constantly updating. One version of background data will be immediately out-of-date during the next updating. What we do provide for users upon request, is the primary input and output data for each of the unit production processes. That data can help users to rebuild similar models if they are using other software tools than GaBi. However, again, as stated in the report in Section 5.2, the data will only be made available upon individual request due to space constraints of this report.
1310-1315	1515-1519	I understand the intent of this paragraph, but it is unnecessarily confusing. There are indeed many names for the two primary approaches. Why not indicate that "avoided burden" is another name for substitution, EOL recycling method, 0/100,	Addressed.

		Recyclability substitution procedure (ILCD). and that "cut-off method" is often used interchangeably with "recycled content method, 100/0. I would make the point about consequential vs. attributional methods in a separate sentence. It seems to me that combining these two points was likely done for the purpose of brevity but is ultimately adds some confusion. Additional citations might be useful here.	
1318	1526	For many, I think the primary concern with the substitution method actually relates to the challenging issue of timescale of emissions. this is particularly troublesome for long-life products like aluminum used in buildings, where the "substitution" or "End of life recycling method" gives credit to emissions savings in the future and allows these future benefits to offset present-day manufacturing emissions. potentially resulting in near zero or negative emissions for a carbon intensive product. The "cut-off" method is therefore also risk-averse in that environmental burdens are strictly linked to the product that causes them, irrespective of potential future use and represent the near-term emissions that many are thinking about when evaluating LCA results. I think it is important to acknowledge this challenge. I agree that the net scrap approach is a reasonable way forward.	Agree. and this is addressed.
1357-1359	1562-1564	It appears from the narrative text that this model is using	Addressed.

		the "closed material loop recycling methodology" also used by the world steel LCA methodology. I think it would be helpful for users of this document seeking to replicate results to also include equations describing the approach in addition to the narrative description.	
1470-1471	1680-1681	I appreciate the inclusion of env. impacts separated out by process. But, for the cradle to grave assessment, why are results not broken out by life cycle stage? It will be very helpful for practitioners to get some transparency into how the EOL allocation procedures described in the section above are mathematically applied and see how impacts are distributed across life cycle stages.	The breakdown of results by major production steps or processes is shown in relevant sections for each product groups. In addition, Appendix 12.3 also lists the breakdown for semi-fabricated products.

10.2.5 Review Results

Review statement from Stephanie Carlisle:

The Environmental Footprint of Semi-Finished Aluminum Products in North America: Life Cycle Assessment Report

The Aluminum Association

December 2020

Reviewer: Stephanie Carlisle, Carbon Leadership Forum

Review completed: July 25, 2021

The goal of external review is to follow ISO 14044 (ISO, 2006b) to ensure that:

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

Reviewer Statement

On the basis of the goals established for this review, the reviewer finds that the study has been carried out in compliance with ISO 14040 and ISO 14044. The overall methodology and the detail of its execution are of high quality and meet the purposes of the study. The LCA models are reported in a comprehensive manner with clear documentation of methodological choices, background data, and scope of assessment. Because the data contained in this report may be used for both cradle-to-gate or cradle-to-grave assessments, the presentation of data and its expression of supply chain variability is appropriate and useful to support a range of manufacturing and end of life scenarios.

Stephanie Carlisle

December 1, 2021

Review statement from Yuan Yao:

Based on the goal of the study, the reviewer concludes that the study is generally consistent to the relevant ISO standards. The study may be disclosed to the public. The report may serve as a background document to support potential EPDs. However, additional revisions and reviews will be needed to conform to the appliable documents and standards relevant to EPDs that were not included in this review process.

Sincerely,

Yuan Yao, Ph.D.

September 7th, 2021

New Haven, CT

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12. Appendix

12.1 List of Companies Provided Data

Table 12-1: Evaluation matrix for data quality assessment

No.	Company	Note
1	Alcoa Corporation	Primary aluminum
2	Arconic Corporation	Recycling, sheet, extrusion
3	Century Aluminum	Primary aluminum
4	Commonwealth Rolled Products	Formally Aleris International, recycling, sheet
5	Constellium	Recycling, sheet, extrusion
6	Howmet	Formally part of Arconic, recycling, sheet, extrusion
7	Hydro Extrusions North America	Recycling, extrusion
8	Hydro Metals North America	Recycling, extrusion billet
9	Jupiter Aluminum	Recycling, sheet
10	JW Aluminum	Recycling, sheet, foil
11	Kaiser Aluminum	Recycling, sheet, extrusion
12	Keymark	Recycling, extrusion
13	Novelis Inc.	Recycling, sheet, foil
14	Real Alloys	Recycling, RSI
15	Rio Tinto	Primary aluminum
16	Reynolds	Foil
17	Scepter Inc.	Recycling, RSI
18	Skana	Recycling, sheet
19	Smelter Service Corporation	Recycling, RSI
20	United Aluminum	Recycling, sheet

12.2 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.

Table 12-2: Evaluation matrix for data quality assessment

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.

Table 12-3: Data quality assessment results

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
Fabrication Ingot Production	1	1	1	1	1
Extrusion	1	1	1	1	1
Automotive Extrusion	1	1	1	1	1
Sheet Rolling	1	1	1	1	1
Automotive Sheet Rolling	1	1	1	1	1
Foil Rolling	1	1	1	1	1
Die Casting	2	4	3	3	2

12.3 Breakdown of LCIA Results for Semi-fabricated Products by Manufacturing Processes

12.3.1 Cradle-to-Gate

Table 12-4: Breakdown of LCIA Results for Generic Extruded Aluminum, Representing 1,000 kg of Aluminum Extrusion

Indicator	Unit	Primary ingot	Recycled ingot (RSI)	Remelting and casting	Extrusion
Non-renewable	MJ	44739.18	304.20	13224.56	12737.35
Renewable	MJ	28556.48	80.10	1559.90	1176.12
Primary energy demand	MJ	73295.66	384.30	14784.46	13913.47
GWP	kg CO2e.	4599.41	22.99	838.69	752.13
Acidification potential	kg SO2e.	20.86	0.07	1.58	1.26
Eutrophication potential	kg N e.	0.47	0.00	0.07	0.09
Smog potential	kg O3e.	176.19	0.78	25.73	23.03

Table 12-5: Breakdown of LCIA Results for Generic Aluminum Sheet, Representing 1,000 kg of Aluminum Sheet

Indicator	Unit	Primary ingot	Recycled ingot (RSI)	Remelting and casting	Sheet rolling
Non-renewable	MJ	24470.34	684.29	13146.85	10585.52
Renewable	MJ	15619.12	180.18	1031.62	1004.85
Primary energy demand	MJ	40089.46	864.47	14178.48	11590.37
GWP	kg CO2e.	2515.67	51.71	794.60	616.34
Acidification potential	kg SO2e.	11.41	0.16	1.30	0.94
Eutrophication potential	kg Ne.	0.26	0.00	0.07	0.06
Smog potential	kg O3e.	96.37	1.75	24.07	18.02

Table 12-6: Breakdown of LCIA Results for Aluminum Foil, Representing 1,000 kg of Aluminum Foil

Indicator	Unit	Primary ingot	Recycled ingot (RSI)	Remelting and casting	Foil rolling
Non-renewable	MJ	26348.29	736.81	14155.80	17694.59
Renewable	MJ	16817.80	194.00	1110.79	1813.08
Primary energy demand	MJ	43166.09	930.81	15266.59	19507.66
GWP	kg CO2e.	2708.73	55.68	855.58	1033.42
Acidification potential	kg SO2e.	12.29	0.17	1.40	1.53
Eutrophication potential	kg Ne.	0.28	0.00	0.07	0.10
Smog potential	kg O3e.	103.77	1.88	25.92	28.03

Table 12-7: Breakdown of LCIA Results for Die Cast Aluminum, Representing 1,000 kg of Aluminum Cast Products

Indicator	Unit	Primary ingot	Recycled ingot (RSI)	Die casting
Non-renewable	MJ	12982.36	11739.45	11258.22
Renewable	MJ	8286.48	3091.03	1397.73
Primary energy demand	MJ	21268.85	14830.48	12655.95
GWP	kg CO2e.	1334.65	887.10	677.23
Acidification potential	kg SO2e.	6.05	2.67	0.93
Eutrophication potential	kg Ne.	0.14	0.08	0.07
Smog potential	kg O3e.	51.13	29.94	15.17

Table 12-8: Breakdown of LCIA Results for Automotive Aluminum Extrusion, Representing 1,000 kg of Aluminum Extrusion

Indicator	Unit	Primary ingot	Remelting and casting	Extrusion
Non-renewable	MJ	30928.69	13122.25	12737.35
Renewable	MJ	19741.41	1264.09	1176.12
Primary energy demand	MJ	50670.11	14386.34	13913.47
GWP	kg CO2e.	3179.62	807.68	752.13
Acidification potential	kg SO2e.	14.42	1.36	1.26
Eutrophication potential	kg Ne.	0.33	0.07	0.09
Smog potential	kg O3e.	121.80	24.18	23.03

Table 12-9: Breakdown of LCIA Results for Automotive Aluminum Sheet, Representing 1,000 kg of Aluminum Sheet

Indicator	Unit	Primary ingot	Remelting and casting	Sheet rolling
Non-renewable	MJ	63936.39	9004.20	10695.47
Renewable	MJ	40809.82	677.88	1015.58
Primary energy demand	MJ	104746.21	9682.08	11711.05
GWP	kg CO2e.	6572.97	549.02	622.79
Acidification potential	kg SO2e.	29.81	0.92	0.95
Eutrophication potential	kg Ne.	0.68	0.05	0.06
Smog potential	kg O3e.	251.80	17.03	18.21

12.3.2 Cradle-to-Grave

Table 12-10: Breakdown of LCIA Results for Generic Aluminum Extrusion, Representing 1,000 kg of Aluminum Extrusion

Indicator	Unit	Primary ingot	Recycled ingot (RSI)	Remelting and casting	Extrusion	EoL
Non-renewable	MJ	44739.18	304.20	13224.56	12737.35	-32815.09
Renewable	MJ	28556.48	80.10	1559.90	1176.12	-23279.79
Primary energy demand	MJ	73295.66	384.30	14784.46	13913.47	-56094.88
GWP	kg CO2e.	4599.41	22.99	838.69	752.13	-3545.80
Acidification potential	kg SO2e.	20.86	0.07	1.58	1.26	-16.78
Eutrophication potential	kg Ne.	0.47	0.00	0.07	0.09	-0.37
Smog potential	kg O3e.	176.19	0.78	25.73	23.03	-137.69

Table 12-11: Breakdown of LCIA Results for Generic Aluminum Sheet, Representing 1,000 kg of Aluminum Sheet

Indicator	Unit	Primary ingot	Recycled ingot (RSI)	Remelting and casting	Sheet rolling	EoL
Non-renewable	MJ	24470.34	684.29	13146.85	10585.52	-9911.07
Renewable	MJ	15619.12	180.18	1031.62	1004.85	-7021.67
Primary energy demand	MJ	40089.46	864.47	14178.48	11590.37	-16932.74
Global warming potential	kg CO2 eq.	2515.67	51.71	794.60	616.34	-1074.34
Acidification potential	kg SO2 eq.	11.41	0.16	1.30	0.94	-5.07
Eutrophication potential	kg N eq.	0.26	0.00	0.07	0.06	-0.11
Smog formation potential	kg O3 eq.	96.37	1.75	24.07	18.02	-41.46

Table 12-12: Breakdown of LCIA Results for Aluminum Foil, Representing 1,000 kg of Aluminum Foil

Indicator	Unit	Primary ingot	Recycled ingot (RSI)	Remelting and casting	Foil rolling	EoL
Non-renewable	MJ	26348.29	736.81	14155.80	17694.59	-12621.99
Renewable	MJ	16817.80	194.00	1110.79	1813.08	-8945.82
Primary energy demand	MJ	43166.09	930.81	15266.59	19507.66	-21567.81
Global warming potential	kg CO2 eq.	2708.73	55.68	855.58	1033.42	-1367.23
Acidification potential	kg SO2 eq.	12.29	0.17	1.40	1.53	-6.45
Eutrophication	kg N eq.	0.28	0.00	0.07	0.10	-0.14

potential						
Smog formation potential	kg O3 eq.	103.77	1.88	25.92	28.03	-52.84

Table 12-13: Breakdown of LCIA Results for Aluminum Die Casting, Representing 1,000 kg of Aluminum Cast Products

Indicator	Unit	Primary ingot	Recycled ingot (RSI)	Die casting	EoL
Non-renewable	MJ	12982.36	11739.45	11258.22	-11395.12
Renewable	MJ	8286.48	3091.03	1397.73	-8111.24
Primary energy demand	MJ	21268.85	14830.48	12655.95	-19506.37
Global warming potential	kg CO2 eq.	1334.65	887.10	677.23	-1232.22
Acidification potential	kg SO2 eq.	6.05	2.67	0.93	-5.84
Eutrophication potential	kg N eq.	0.14	0.08	0.07	-0.13
Smog formation potential	kg O3 eq.	51.13	29.94	15.17	-47.85

Table 12-14: Breakdown of LCIA Results for Automotive Aluminum Extrusion, Representing 1,000 kg of Aluminum Extrusion

Indicator	Unit	Primary ingot	Remelting and casting	Extrusion	EoL
Non-renewable	MJ	30928.69	13122.25	12737.35	-19330.15
Renewable	MJ	19741.41	1264.09	1176.12	-13711.25
Primary energy demand	MJ	50670.11	14386.34	13913.47	-33041.40
Global warming potential	kg CO2 eq.	3179.62	807.68	752.13	-2089.66
Acidification potential	kg SO2 eq.	14.42	1.36	1.26	-9.88
Eutrophication potential	kg N eq.	0.33	0.07	0.09	-0.22
Smog formation potential	kg O3 eq.	121.80	24.18	23.03	-81.03

Table 12-15: Breakdown of LCIA Results for Automotive Aluminum Sheet, Representing 1,000 kg of Aluminum Sheet

Indicator	Unit	Primary ingot	Remelting and casting	Sheet rolling	EoL
Non-renewable	MJ	63936.39	9004.20	10695.47	-52754.10
Renewable	MJ	40809.82	677.88	1015.58	-37426.26
Primary energy demand	MJ	104746.21	9682.08	11711.05	-90180.36
Global warming potential	kg CO2	6572.97	549.02	622.79	-5699.94

	eq.				
Acidification potential	kg SO2 eq.	29.81	0.92	0.95	-26.99
Eutrophication potential	kg N eq.	0.68	0.05	0.06	-0.60
Smog formation potential	kg O3 eq.	251.80	17.03	18.21	-221.50

12.4 Bio of External Peer Reviewer (s)

12.4.1 Bio of Stephanie Carlisle

Stephanie Carlisle is a Senior Researcher at the Carbon Leadership Forum where she leads collaborative development of open-access LCA data, tools, and methods to support the building sector in radically decarbonizing construction. Her work brings together diverse stakeholders from design, industry, land management, manufacturing, labor, and policy to find new approaches to climate justice.

Prior to joining the CLF, she was a Principal at KieranTimberlake where she helped develop Tally, a whole building LCA tool, led the firm's carbon accounting, and worked to implement strategies that address climate and health impacts of building materials. She is Co-Editor-in-Chief of Scenario Journal, and a lecturer at the Weitzman Schools of Design at the University of Pennsylvania where she teaches courses in life cycle assessment, building materials, and urban ecology. Stephanie received a Master’s in Environmental Management from the Yale School of Forestry, an M. Arch from Yale School of Architecture, and a BA in Comparative Religion from Wesleyan University.

12.4.2 Bio of Yuan Yao

Yuan Yao is an Assistant Professor of Industrial Ecology and Sustainable Systems at the Yale School of the Environment. Her research is motivated by the increasing need for sustainable solutions that can support industrial development without compromising the environment or depleting the resources for future generations. Her research investigates how emerging technologies and industrial development will affect the environment. She uses interdisciplinary approaches in industrial ecology, sustainable engineering, and machine learning to develop systems analysis tools to support engineering and policy decisions towards sustainability. She develops new methods and integrated modeling frameworks to assess, advance, and optimize industrial systems for improved environmental and societal outcomes. Current research projects focus on the bioeconomy and sustainable production.

Dr. Yao received the National Science Foundation Faculty Early Career Development Award (CAREER). She has been named to the American Institute of Chemical Engineers "35 Under 35" list for emerging leaders in chemical engineering. Dr. Yao also serves as the Associate Editor for Resources, Conservation & Recycling, a leading journal in sustainable management and conservation of resources. Dr. Yao has been leading collaborative projects with U.S. national labs, private companies, and non-profits.

She got her Ph.D. degree in Chemical Engineering from Northwestern University and a B.S. degree in Metallurgical Engineering from Northeastern University in China. She also has a Management for Scientists and Engineers from Kellogg School of Management.