ANL/ESD-15/12

Updated Life-Cycle Analysis of Aluminum Production and Semi-Fabrication for the GREET Model

Energy Systems Division

ANL/ESD-15/12

Updated Life-Cycle Analysis of Aluminum Production and Semi-Fabrication for the GREET Model

by
Qiang Dai, Jarod C. Kelly, Andrew Burnham, and Amgad Elgowainy
Energy Systems Division, Argonne National Laboratory

September 2015

CONTENTS

ACRONYMS v

1 INTRODUCTION 1

2 ALUMINUM PRODUCTION 2

2.1 Primary Aluminum Production 2
2.1.1 Process Description 2
2.1.2 Process Emissions 4
2.1.3 Summaries 5
2.2 Secondary Aluminum Production 9
2.3 Aluminum Semi-Fabrication 11
2.3.1 Wrought Aluminum Production 11
2.3.2 Cast Aluminum Production 14

3 RESULTS AND DISCUSSION 17

APPENDIX A: CALCULATION OF THE ELECTRICITY MIX REPRESENTING U.S. CONSUMPTION OF PRIMARY AL 19

APPENDIX B: LCI TABLES FOR ALUMINUM PRODUCTION 23

REFERENCES 34

FIGURES

1 Life-cycle of aluminum products 3

2 Process flow diagram for aluminum sheet production 12

3 Process flow diagram for aluminum casting 15

TABLES

1 LCI of primary aluminum production (MMBtu, short ton, and gram per short ton Al) 6
2 Total energy comparison for 1 short ton of primary aluminum 7
3 2010 electricity mix for aluminum smelters and U.S. national average 7

TABLES (CONT.)

4 LCI of secondary aluminum production (MMBtu, short ton, gram per short ton of Al).......... 10

5 LCI of wrought aluminum production (MMBtu, short ton, gram per short ton of aluminum product).. 13

6 Total energy comparison for 1 short ton of aluminum product... 14

7 Energy consumption for shape casting (MMBtu/short ton) 16

8 Fluorides and chlorides emissions for aluminum production (gram/short ton)........................ 17

A-1 2010 electricity mix for aluminum used in the U.S... 20

A-2 2013 electricity mix for aluminum used in the U.S... 20

A-3 2010 electricity mix for aluminum used in the U.S., considering mixed flow of primary and secondary aluminum 22

A-4 2013 electricity mix for aluminum used in the U.S., considering mixed flow of primary and secondary aluminum 22

A-5 Electricity mix for aluminum smelting in North America.. 22

B-1 LCI of bauxite mining, normalized to 1 ton of primary aluminum produced 23

B-2 LCI of bauxite refining, normalized to 1 ton of primary aluminum produced..................... 24

B-3 LCI of anode production, normalized to 1 ton of primary aluminum produced.................. 25

B-4 LCI of alumina reduction, for 1 ton of primary aluminum produced.................................. 26

B-5 LCI of primary ingot casting, for 1 ton of primary ingot produced..................................... 27

B-6 LCI of scrap preparation, normalized to 1 ton of secondary ingot produced 28

B-7 LCI of secondary ingot casting, for 1 ton of secondary ingot produced.............................. 29

B-8 LCI of extrusion, for 1 ton of extruded aluminum.. 30

B-9 LCI of hot rolling, for 1 ton of hot-rolled aluminum.. 31

B-10 LCI of cold rolling, for 1 ton of cold-rolled aluminum 32

B-11 Reported emission, GREET estimated combustion emission and estimated process emission for 1 short ton of primary aluminum 33

B-12 Reported emission, GREET estimated combustion emission and estimated process emission for 1 short ton of secondary aluminum and aluminum semi-products 33

ACRONYMS

AA	The Aluminum Association
DOE	U.S. Department of Energy
EAA	European Aluminum Association
EPA	U.S. Environmental Protection Agency
GHG	greenhouse gas
IAI	International Aluminum Institute
LCA	life-cycle analysis
LCI	life-cycle inventory
PM	particulate matter
VOC	volatile organic compound
USGS	U.S. Geological Survey

1 INTRODUCTION

As the second most abundant metallic element in the earth's crust, aluminum is also the second most used metal after iron. Due to its low density, good malleability and corrosion resistance, aluminum is widely used in many important sectors of the economy, such as transportation, containers and packaging, buildings and construction, electronics and consumer durables. However, the production of primary aluminum is energy-intensive, and contributes significantly to greenhouse gas (GHG) emissions. Since the global demand for aluminum has risen from 11.85 million metric tons (Mt) in 1972 to 39.66 Mt in 2010, and is expected to grow annually by 4% for the next two decades (Nappi, 2013), the life-cycle environmental burden associated with the production of aluminum and aluminum products is worth revisiting from a life-cycle perspective as new technology and data become available. Please note that throughout this report metric tons are referenced with "t" and short tons are referenced with "ton".

This report serves as an update for the life-cycle analysis (LCA) of aluminum production based on the most recent data representing the state-of-the-art of the industry in North America. The 2013 Aluminum Association (AA) LCA report on the environmental footprint of semi-finished aluminum products in North America provides the basis for the update (The Aluminum Association, 2013). The scope of this study covers primary aluminum production, secondary aluminum production, as well as aluminum semi-fabrication processes including hot rolling, cold rolling, extrusion and shape casting. This report focuses on energy consumptions, material inputs and criteria air pollutant emissions for each process from the cradle-to-gate of aluminum, which starts from bauxite extraction, and ends with manufacturing of semi-fabricated aluminum products. The life-cycle inventory (LCI) tables compiled are to be incorporated into the vehicle cycle model of Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model for the release of its 2015 version.

2 ALUMINUM PRODUCTION

The United States is the world's fourth largest aluminum producer. According to statistics from the United States Geological Survey (USGS), in 2013 1.95 Mt of primary aluminum was produced in the U.S., and 3.48 Mt of secondary aluminum was recovered from scrap, including 1.85 Mt from new scrap and 1.63 Mt from old scrap (USGS 2015a). In addition to domestic production, 4.16 Mt of crude (ingot, pig, slab, etc.) and semicrude (plates, sheets, bars, castings, etc.) aluminum was also imported, mostly from Canada (63%), Russia (5%), United Arab Emirates (5%) and China (4%), for consumption in the U.S. Taking into account the total exports of 3.39 Mt, the apparent domestic consumption (defined as "domestic primary metal production + recovery from old scrap + net import reliance" by USGS) of aluminum in 2013 amounted to 4.53 Mt, for which the transportation sector consumes 36%, packaging 23%, building 14%, electrical 9%, machinery 8%, and consumer durables 7%, respectively (USGS 2013).

The life-cycle of aluminum products is depicted in Figure 1. This report covers all stages except for product manufacturing and product use. Primary aluminum is produced from bauxite. Secondary aluminum is recovered from aluminum scrap, including that recycled from spent aluminum products (a.k.a. old scrap), and that collected from semi-fabricators including rolling mills, foundries and extrusion facilities, as well as from manufacturers of aluminum products (a.k.a. new scrap).

2.1 PRIMARY ALUMINUM PRODUCTION

2.1.1 Process Description

Primary aluminum production starts with mining of bauxite, which is the raw material for aluminum. Once extracted from open-pit mines, bauxite is washed to removed impurities, dried and then shipped to the refinery. The U.S. almost entirely relies on imported bauxite for primary aluminum production. Jamaica, Guinea, and Brazil together supplied 91% of U.S. bauxite imports during 2010-2013 (USGS 2015b).

In the refinery, bauxite is converted to alumina via the Bayer process, in which bauxite is ground and reacted with a liquor containing dissolved soda ash (sodium carbonate, Na_2CO_3) and caustic soda (sodium hydroxide, NaOH). The resulting slurry is then heated and pumped to digesters for iron and silicon impurities to precipitate out as red mud. The resultant sodium aluminate ($NaAlO_2$) concentrate is further filtered and seeded to form alumina trihydrate ($Al_2O_3.3H_2O$) crystals. Finally, the water content is removed in a calciner to produce pure alumina (aluminum oxide, Al_2O_3) (Sleppy, 2000). Compared with bauxite, the U.S. only imports 46% of its total alumina consumption, mostly from Australia, Suriname and Brazil (USGS 2015b).

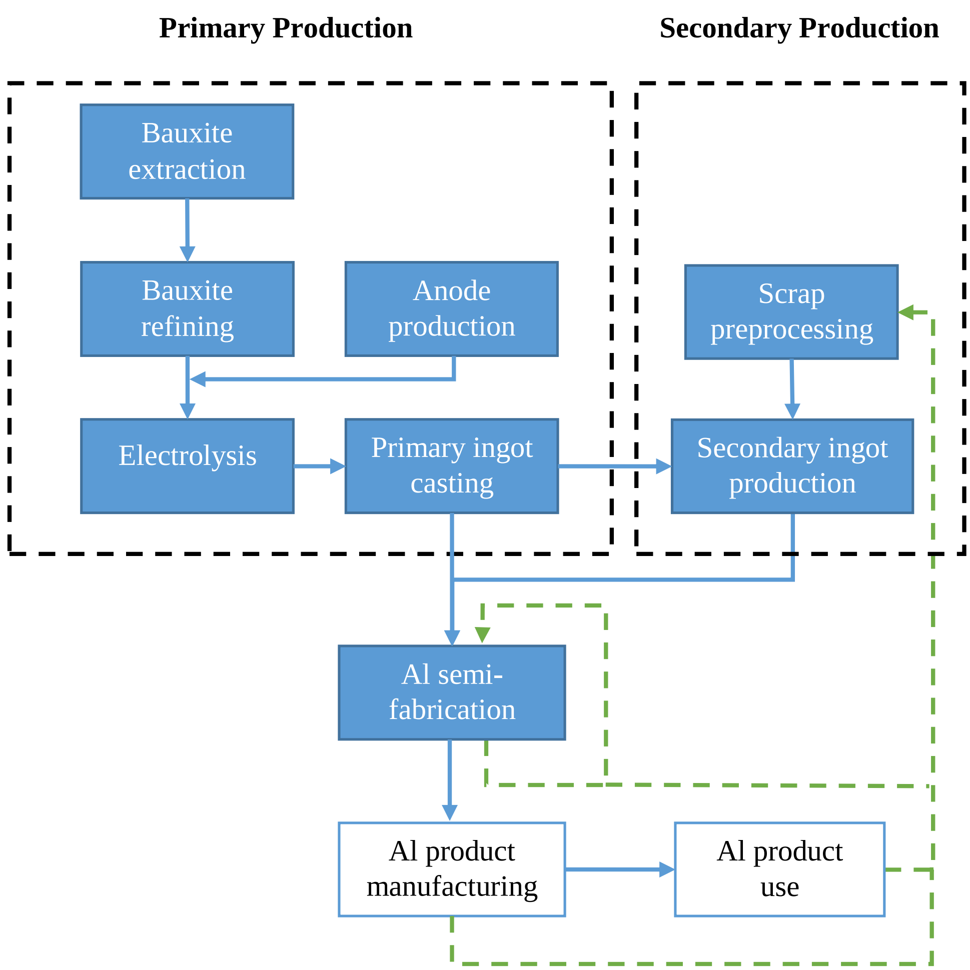

FIGURE 1 Life-cycle of aluminum products. Green dashed lines represent recycling practices. White boxes represent processes not modeled in this study.

The refined alumina is subsequently sent to a smelter for production of primary aluminum via the Hall-Heroult electrolysis process. Since the process also requires an anode as an operating material, the anode needs to be produced first, in the form of prebake cells or Soderberg cells. Prebake technology provides higher efficiency and better emission control, and has gradually replaced Soderberg technology in recent years. As of 2010, prebake facilities accounted for 95% of the primary aluminum production in North America (The Aluminum Association 2013). Therefore, in this report only prebake technology is examined. In a prebake facility, carbon blocks are extruded from a paste formed by blending coal pitch with calcined and ground petroleum coke, and then sent to a furnace to be baked.

In the smelter, alumina is dissolved in a molten cryolitic bath to form the electrolyte. As electric current flows through the electrolyte, alumina is broken down into metallic aluminum and oxygen. Oxygen reacts with the carbon anode and forms CO and CO_2, while the molten aluminum is tapped out of the pot and delivered to a cast house or semi-fabricator.

In the cast house, alloying agents are added to the molten aluminum in a holding furnace to adjust the metal composition. Fluxing is carried out next, in which nitrogen and chlorine gases are slowly bubbled through the molten metal to remove impurities and gas content. After the impurities floating on the molten aluminum, known as dross, are skimmed off, the refined metal is cast into primary ingots.

LCI data pertaining to primary aluminum production processes are compiled based on the input-output tables for each process provided in the 2013 AA report (The Aluminum Association, 2013). The 2013 AA report is the outcome of an extensive survey of aluminum manufactures in North America, and the data reported is therefore considered a good representation of industrial averages in North America for 2010. Aluminum data in the 2014 GREET model was largely based on two prior LCA reports for aluminum, one prepared by AA (The Aluminum Association, 1998), and the other commissioned by AA (PE Americas, 2010). Although the 2010 PE report focused on the production of aluminum cans, whereas the 1998 and the 2013 AA reports were industry-wide, they all presented the industry averages for primary aluminum production in North America for their respective temporal scopes. Moreover, all of the three reports employed the same methodology, which makes the update a more inherently consistent practice.

2.1.2 Process Emissions

In addition to material and energy flows, the 2013 AA report also lists emissions for each process. It should be noted that “process emissions” used throughout the report refer to emissions arising from on-site activities that are not related to fuel combustion. As the 2010 PE report did not provide process emission data, existing emissions of criteria air pollutants for primary aluminum production in the 2014 GREET model were either based on stoichiometric calculation or obtained from a 1998 DOE report. To update the 2014 GREET model with data from the 2013 AA report, it is essential to know where the emissions came from, how they were measured or calculated, and if the reported process emissions included those from fuel combustion particularly, as fuel combustion emissions are already accounted for in GREET.

Based on personal communication with Mr. Marshall Wang from the Aluminum Association, it was ascertained that the emissions listed in their 2013 report included the direct combustion emissions from fuel used at the facilities for each of the aluminum production processes. Mr. Wang commented that aluminum smelters, foundries and other semi-fabricators were required by EPA to report their NO_x, SO_x, and PM emissions. Measurements for these emissions are usually taken at the stack, and therefore inevitably include emissions from burning fossil fuels at the furnaces (M. Wang, personal communication, February 13, 2015).

To avoid double counting, the process emissions of NO_x, SO_x, and PM, referred to as non-combustion emissions in GREET, were calculated by subtracting combustion emissions of natural gas, residual oil and coal consumed in each process from the reported emissions for that process. As the exact combustion emissions from each process were not known, they were estimated using emission factors for fuel combustion at industrial boilers from the 2014 GREET model. There were three cases where the reported emissions were smaller than the calculated fuel combustion emissions: NO_x and SO_x emissions for cold rolling, and NO_x emission for extrusion. Given that the differences were no bigger than 50 grams/short ton (abbreviated to ton hereafter) of product for NO_x emissions, and was 0.2 grams/ton of product for SO_x, it was not likely that using 2014 GREET emission factors would systematically overestimate the combustion emissions at these plants. It was therefore assumed that fuel combustion was the only source of these emissions, and the corresponding process emissions were set to zero.

2.1.3 Summaries

The LCIs derived from the 2013 AA report for each process concerning primary aluminum production are summarized in Table 1. As a comparison, the LCIs extracted from the 2013 European Aluminum Association (EAA) report, which represent the industrial average for European aluminum production in 2010 (European Aluminum Association, 2013), are listed side by side with the AA numbers.

It can be observed from Table 1 that energy and material consumptions given in both reports are quite similar. However, the emission numbers differ in the two reports, sometimes significantly. This is likely due to different electricity mixes used for alumina reduction, emission standards and corresponding control technologies.

Compared with energy consumption numbers in the 2014 GREET model as shown in Table 2, no drastic changes in energy consumption are observed. Nonetheless, it should be noted that there have been noticeable changes in sources of energy since the 2010 PE report, especially in sources for electricity consumed in the electrolysis process. Due to the electricity-intensive electrolysis process, some of the aluminum smelters in North America do not draw electricity directly from the grid. Rather, they build their own power plants on-site. Therefore, the U.S. national grid mix would not be representative of the electricity consumed at the aluminum smelters. The aluminum model in the 2014 version of GREET includes the U.S. national grid mix as an option in case the users want to explore it. However, the 2006 North American smelter mix reported in PE 2010 is used as the default in that GREET version. As stated previously, the smelter electricity mix changes over time. It was observed that the share of hydroelectric power at aluminum smelters in North America had grown from 69.4% in 2006 to 75.1% in 2010, while the share of coal electricity had experienced a moderate decrease from 29.7% to 24.0% (IAI 2015a). The shares of electricity produced from natural gas and nuclear remained relatively unchanged.

TABLE 1 LCI of primary aluminum production (MMBtu, short ton, and gram per short ton Al)

	Units per ton Al ingot	Bauxite mining		Bauxite refining		Anode production		Alumina reduction		Primary ingot casting	
		AA 2013	EAA 2013	AA 2013	EAA 2013	AA 2013	EAA 2013	AA 2013	EAA 2013	AA 2013	EAA 2013
Intermediate material	ton	5.575	4.326	1.935	1.922	0.429	0.415	1.000	1.000	1.020	1.019
Resid. oil	MMBtu	0.21	0.03	2.95	9.62	0.52	0.13	---	---	0.11	0.16
Diesel	MMBtu	0.35	0.05	0.003	0.002	0.10	0.005	---	---	0.03	0.04
Gasoline	MMBtu	---	---	---	---	---	---	---	---	---	---
Natural gas	MMBtu	---	---	12.91	7.62	0.71	0.77	---	---	0.66	1.16
Coal	MMBtu	---	---	1.34	---	---	---	---	---	---	---
Liquefied petroleum gas	MMBtu	---	---	---	---	---	---	---	---	0.003	0.003
Electricity	MMBtu	0.02	0.01	0.64	1.08	0.17	0.14	46.8	46.1	0.21	0.30
Total energy	MMBtu	0.58	0.09	17.84	18.32	1.49	1.04	46.8	46.1	1.01	1.67
Sodium Hydroxide (50%)	ton	---	---	0.31	0.11	---	---	---	---	---	---
Lime	ton	---	---	0.08	0.04	---	---	---	---	---	---
Coke input	ton	---	---	---	---	0.35	0.36	0.006	0.007	---	---
Steel sheet	ton	---	---	---	---	0.003	0.004	0.004	0.004	---	---
NO_x	g	---	---	1,194	1,935	217.7	169.4	235.9	399.2	65.3	190.5
PM_{10}	g	859.8	667.2	983	244.1	92.9	94.1	1,760	762	33.6	36.3
$PM_{2.5}$	g	429.9	333.6	491.5	122.1	46.5	47.1	880	381	16.8	18.1
SO_x	g	---	---	4,213	4,673	1,186	289.9	13,862	6,713	99.8	136.1
CF_4	g	---	---	---	---	---	---	69.8	36.3	---	---
C_2F_6	g	---	---	---	---	---	---	9.6	3.6	---	---

Note

1. The amount of intermediate material represents the amount of output from each production process needed for the production of 1 ton of primary aluminum. For instance, according to AA 2013, 5.575 tons of bauxite ore, which is the output from the bauxite mining process, is needed to produce 1 ton of primary aluminum.

2. Emissions are original numbers, which include fuel combustion emissions.

TABLE 2 Total energy comparison for 1 short ton of primary aluminum

Total energy (MMBtu)	Bauxite extraction	Bauxite refining	Anode production	Alumina reduction	Primary ingot casting
2014 GREET	0.299	16.973	1.207	48.133	1.452
Updated	0.577	17.835	1.486	46.778	1.006

In addition to temporal variations, even more considerable variations of electricity mix exist in smelters across different regions, as can be observed from Table 3. The regional variations in the environmental impacts of primary aluminum production due to different sources of consumed electricity has been investigated by a few studies. Colett *et al* examined the impact of electricity allocation in primary aluminum production on the environmental footprints of produced aluminum (Colett *et al*, 2015). Although they focused primarily on the GHG emissions, since energy consumption and GHG emission are often highly correlated, their findings also provide insights into how the electricity mix used in a LCA study would affect the resulting total energy consumption, especially for products that are electricity-intensive to produce, such as aluminum.

TABLE 3 2010 electricity mix for aluminum smelters and U.S. national average

	Europe (EAA 2013)	North America (AA 2013)	Canada[a]	U.S.[b]	U.S. national grid (EPA 2014a)
Hydro	54.0%	75.1%	100.0%	32.2%	6.2%
Coal	17.0%	24.0%	0.0%	65.2%	44.8%
Oil	1.0%	0.0%	0.0%	0.0%	1.0%
Gas	10.0%	0.5%	0.0%	1.3%	24.0%
Nuclear	18.0%	0.5%	0.0%	1.3%	19.6%

[a] Inferred from Green 2007, verified by checking Canadian smelter locations and local electricity mixes obtained from Statistics Canada (Statistics Canada 2014).

[b] Calculated by subtracting Canadian power consumption from that of North America based on International Aluminum Institute statistics for North America primary aluminum smelting energy intensity and Canadian primary aluminum production (IAI 2015a).

As can be observed from Table 2, bauxite refining and alumina reduction are the two most energy-intensive production stages for primary aluminum. Electricity only accounts for 3.6% of the energy consumption for bauxite refining, whereas alumina reduction is exclusively powered by electricity (The Aluminum Association, 2013). By examining the effect of using emission factors representative of localized electricity consumption by an aluminum smelter, it was discovered that the calculated GHG emissions associated with primary aluminum production differed significantly among smelters, ranging from 4.3 kg to 30.0 kg CO_2-eq per kg (3,901,000 to 27,216,000 grams CO_2-eq per ton) of primary aluminum ingot (Colett *et al*, 2015). Production-weighted GHG averages of 19.0 and 19.9 kg CO_2-eq per kg (17,237,000 and

18,053,000 grams CO_2-eq per ton) were also reported, for aluminum ingot produced in the U.S., corresponding to two different electricity allocation methods employed (Colett et al, 2015). Compared with the cradle-to-gate GHG emission of 10.2 kg CO_2-eq per kg (9,253,000 grams CO_2-eq per ton) of aluminum ingot estimated by the 2014 GREET model, and the 9.0 kg CO_2-eq per kg (8,165,000 grams CO_2-eq per ton) of aluminum ingot GHG intensity calculated based on the updated 2010 data from the 2013 AA report, the geographical scope of both of which was North America, it can be asserted that fuel mix of electricity for aluminum electrolysis dictates the environmental impacts of primary aluminum production. Choosing an electricity mix that is representative of the electricity consumed at the smelters is therefore crucial to the LCA of primary aluminum.

For this reason, four electricity mixes for aluminum electrolysis are included in this update, representing North American production, U.S. domestic production, U.S. domestic consumption, and U.S. national grid respectively. Considering that the United States imports more than half of its consumed aluminum, and over half of the imported aluminum is from Canada, the North America smelter mix reported by the International Aluminum Institute is set as the default mix in GREET because of data quality. To account for the aluminum imported from other countries, the U.S. domestic consumption is incorporated as an approximation for the electricity consumed to produce the aluminum used in the U.S. This mix is developed from a market-weighted average of domestically produced aluminum and imported aluminum. The calculation of this U.S. Al market electricity mix is elaborated in Appendix A.

2.2 SECONDARY ALUMINUM PRODUCTION

Secondary aluminum production begins with collecting scrap, both new and old, from aluminum semi-fabricators, aluminum product manufacturers, and post-consumer aluminum goods.

After being separated from other materials by means of hand-sorting, magnetic separation, air classification and other separation technologies, recycled aluminum scrap is cleaned as it often contains oil, grease and other contaminants. Scrap cleaning typically involves de-oiling, de-coating, de-lacquering, paint removal, sweating and drying. Other processing steps such as shredding, shearing and crushing may also be deployed. The cleaned and pre-processed scrap is then fed to a melting furnace where the scrap is melted, purified and finally cast into secondary ingots.

One issue of environmental concern with secondary aluminum production is the material input of primary aluminum. The use of primary aluminum in secondary aluminum production seems counterintuitive. However, it is a universal practice among secondary aluminum manufactures. Recycled aluminum scrap contains the alloying agents added during primary production. It is very difficult to remove these impurities during the remelting and refining processes for secondary aluminum production (Reck and Graedel, 2012). In order to achieve the desired metal composition, primary aluminum is added to the furnace to dilute the alloy mix and thereby “sweeten” the melt. Compared with cast aluminum, wrought aluminum is lower in alloy concentration, and therefore can be recycled into cast aluminum.

However, due to supply constraints of secondary wrought aluminum, on a global level primary aluminum accounted for 25% of the input metal into refiners for the production of secondary cast aluminum in 2007. In contrast, aluminum remelters required a 5% “sweetener” input for the production of secondary wrought aluminum (Cullen *et al*, 2013). In the 2013 AA report, 65.4 kg (0.072 ton) of primary aluminum was used for the production of 1 metric ton (1.102 ton) of secondary aluminum. Adding the 14.5 kg (0.016 ton) of alloy elements which is also modeled as primary aluminum in this study, the sweetener content is estimated to be 8.0% (The Aluminum Association, 2013). The aluminum model in the 2014 version of GREET does not address this issue, and the inclusion of primary aluminum input in secondary aluminum production increases the total energy consumption for secondary aluminum ingot from 5.3 MMBtu/ton to 15.5 MMBtu/ton, and GHG emissions from 365 kg CO_2-eq/ton to 1,029 kg CO_2-eq/ton. Nonetheless, compared with the environmental footprints of 108 MMBtu total energy consumption and 6,938 kg CO_2-eq GHG emissions for 1 ton of primary aluminum ingot, secondary aluminum still provides significant impacts reduction from that of primary aluminum.

Detailed material and energy inputs for secondary aluminum production are listed in Table 4. Again, along with data obtained from the AA report, data taken from the EAA report is also shown. LCI data for scrap preparation is not found in the EAA report, though.

TABLE 4 LCI of secondary aluminum production (MMBtu, short ton, gram per short ton of Al)

	Units per ton Al ingot	Scrap pretreatment AA 2013	Secondary Al ingot casting AA 2013	Secondary Al ingot casting EAA 2013
Intermediate material	ton	1.042	0.968	1.041
Resid. oil	MMBtu	---	---	0.07
Diesel	MMBtu	---	---	0.06
Natural gas	MMBtu	0.746	4.118	3.04
Liquefied petroleum gas	MMBtu	---	---	0.13
Electricity	MMBtu	0.345	0.342	0.38
Total energy	MMBtu	1.092	4.460	3.67
Sodium Hydroxide (50%)	ton	---	0.0004	---
Lime	ton	0.001	0.004	---
Steel Sheet	ton	---	0.0001	---
Primary aluminum	ton	---	0.080	---
SO_2	g	---	21.56	58.70
NO_x (as NO_2)	g	---	192.7	320.5
CO_2	g	---	6.61	---
CH_4	g	---	0.354	---
VOC	g	---	80.02	51.71
PM_{10}	g	---	256.7	47.63
$PM_{2.5}$	g	---	128.3	23.81
N_2O	g	---	0.336	---

Note
1. The amount of intermediate material represents the amount of output from each production process needed for the production of 1 ton of secondary aluminum.
2. Emissions are original numbers, which include fuel combustion emissions.

2.3 ALUMINUM SEMI-FABRICATION

Aluminum semi-fabrication technologies covered by GREET include extrusion, hot rolling, cold rolling, shape casting and stamping. The first four technologies are investigated in this update. Since no additional information was found for stamping, the existing LCI data for stamping in the 2014 GREET model was retained.

2.3.1 Wrought Aluminum Production

Wrought aluminum is cast into ingots or billets initially, and then mechanically worked into the desired form. Semi-fabrication processes related to wrought aluminum production involve extrusion, hot rolling and cold rolling. Both hot rolling and cold rolling are flat-rolling technologies that convert ingots and slabs into aluminum sheets and foils. A detailed process flow is depicted in Figure 2, which was prepared based on process descriptions in the 2008 AA report on rolling aluminum (The Aluminum Association 2008).

In the extrusion process, billets are preheated, sheared and deposited into a hydraulic press. The heated billets are then squeezed through a steel die by the press to form shapes, which are subsequently extruded into desired length, followed finally by water quenching or cooling.

The LCIs for aluminum sheet rolling and extrusion compiled based on the 2013 AA report and EAA report are presented in Table 5. Total energy consumption for secondary aluminum production and aluminum semi-fabrication obtained from the 2014 GREET model and that calculated from the updated data are shown in Table 6. The data show that energy consumption for secondary aluminum production and aluminum semi-fabrication increased substantially from 2006 to 2010.

The increased energy consumption for aluminum semi-fabrication can be explained by the inclusion of scrap/metal melting and casting into the unit processes of hot rolling, cold rolling and extrusion in the 2013 AA report. This was done intentionally to avoid allocation, as most aluminum semi-fabricators in North America receive a mixture of primary aluminum, secondary aluminum and scrap as the feed material. The metal received by the semi-fabricators is not necessarily in the desired form for subsequent fabrication, and may need to be processed, remelted and recast into ingots before it can be worked into wrought aluminum products, which consequently drives up the energy consumption.

As evident in the EAA report, compared with the base case where aluminum sheet is produced solely from rolling ingot, adding in 406 kg (0.448 ton) of clean aluminum scrap increased the energy consumption by 1.492 MMBtu for 1 ton of aluminum sheet produced. Similarly, the melting and casting of 323 kg (0.356 ton) scrap charge in aluminum extrusion raised the total energy by 1.433 MMBtu for 1 ton of extruded product (European Aluminum Association, 2013). The reason for the increased energy consumption reported in the 2013 AA study for scrap preparation and secondary ingot casting, however, is not clear.

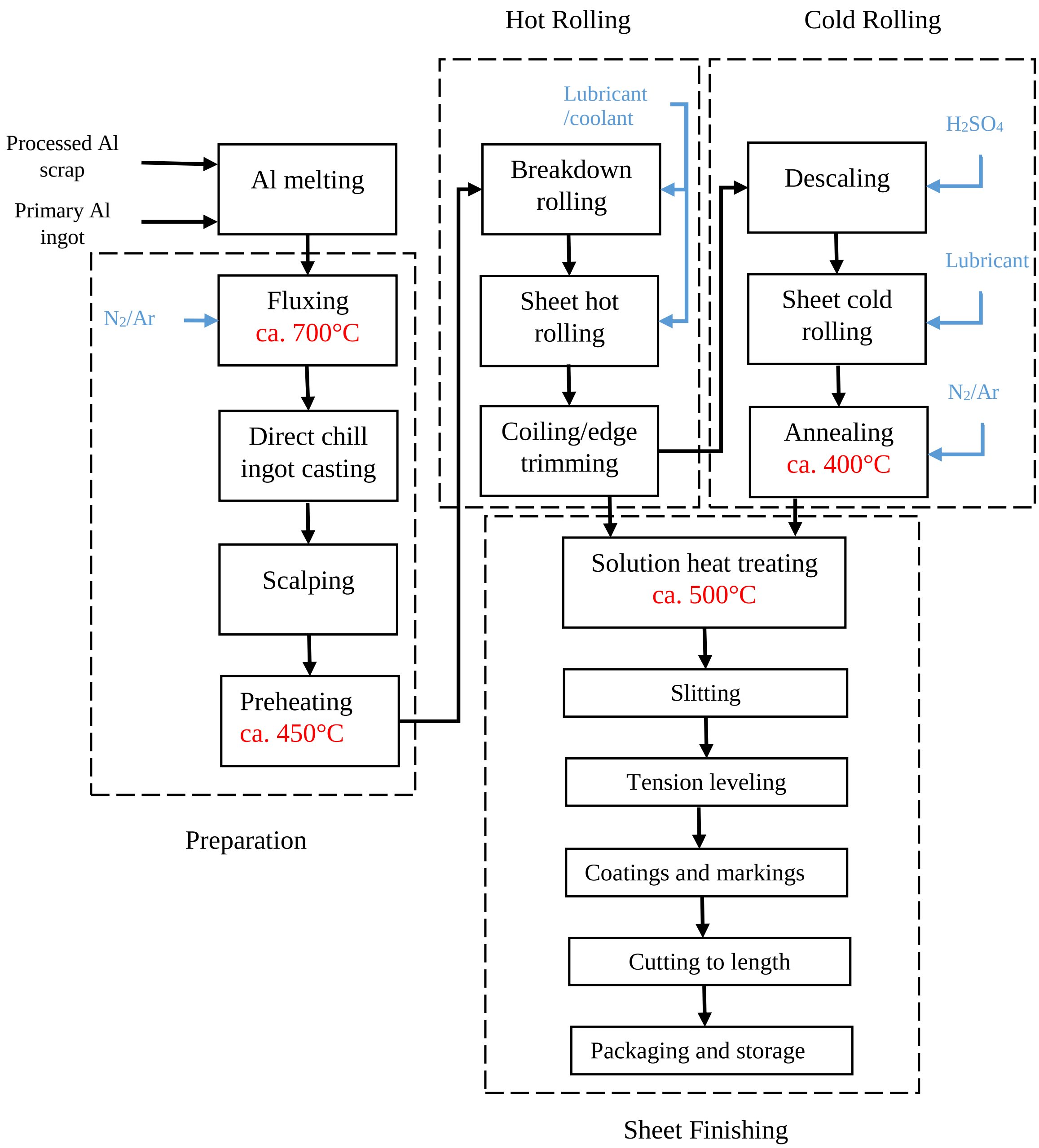

FIGURE 2 Process flow diagram for aluminum sheet production

TABLE 5 LCI of wrought aluminum production (MMBtu, short ton, gram per short ton of aluminum product)

	Units per ton Al product	Hot rolling AA 2013	Cold rolling AA 2013	Sheet production EAA 2013[a]	Sheet production EAA 2013[b]	Extrusion AA 2013	Extrusion EAA 2013[a]	Extrusion EAA 2013[b]
Intermediate material	ton	1.035	1.000	1.003	1.003	1.000	1.000	1.000
Resid. oil	MMBtu	---	---	---	0.027	---	0.014	0.014
Diesel	MMBtu	---	---	0.001	0.024	---	0.057	0.066
Natural gas	MMBtu	3.278	1.888	1.606	2.839	5.288	1.924	2.865
Coal	MMBtu	---	---	0.000	0.000	---	---	---
Liquefied petroleum gas	MMBtu	---	---	0.017	0.069	---	---	---
Electricity	MMBtu	0.351	1.134	1.604	1.761	0.610	2.486	2.969
Total energy	MMBtu	3.629	3.022	3.228	4.720	5.897	4.481	5.914
Sodium Hydroxide (50%)	ton	0.00002	0.0001	---	---	0.008	0.024	0.024
Lime	ton	0.0002	0.0003	---	---	---	---	---
Steel Sheet	ton	0.00001	0.0002	0.0004	0.0004	0.0008	0.0003	0.0003
NO_x	g	205.2	55.34	254.0	381.0	142.4	63.50	117.9
PM_{10}	g	110.3	60.15	18.14	36.29	---	---	18.14
$PM_{2.5}$	g	55.16	30.07	9.07	18.14	---	---	9.07
SO_x	g	7.44	0.27	9.07	27.22	6.44	18.14	27.22
CH_4	g	---	1.09	290.3	308.5	---	---	---
VOC	g	264.7	240.2	---	---	256.8	9.07	9.07

Note

1. Sheet production in EAA represents the combination of hot rolling and cold rolling

[a] Production without aluminum scrap charge

[b] Production with clean aluminum scrap charge

2. The amount of intermediate material represents the inverse of material efficiency for each semi-fabrication process.

3. Emissions are original numbers, which include fuel combustion emissions.

TABLE 6 Total energy comparison for 1 short ton of aluminum product

Total energy (MMBtu)	Scrap preparation	Secondary ingot casting	Hot rolling	Cold rolling	Extrusion
2014 GREET	0.623	2.898	1.874	1.927	3.823
Updated	1.092	4.460	3.629	3.022	5.897

2.3.2 Cast Aluminum Production

Aluminum shape casting is the process in which molten aluminum is poured into sand or metal molds to create products of desired shapes once solidified. It is an important process of aluminum semi-fabrication. According to the USGS, in 2013 the U.S. shipped 2.00 Mt of cast aluminum, while the shipped wrought aluminum totaled 6.54 Mt. Among the shipped cast aluminum, 62% was produced by die casting, 30% by permanent and semi-permanent mold casting, and 8% by sand casting (USGS, 2013). The typical aluminum casting process, as described in a DOE report on metal casting (DOE, 1999), is shown in Figure 3.

The 2013 AA report did not provide an input-output table for aluminum shape casting, due to a lack of producer response to a survey by the AA. The existing LCI in the 2014 GREET model for aluminum shape casting was based on the 1998 AA report. However, in our personal communication with Mr. Wang, he commented that the energy consumption of 7.569 MMBtu/ton product in the 1998 report was too high, and therefore was not a good representation of current technology. He further disclosed that a North American aluminum foundry he contacted reported an energy consumption that was only 1/3 of what was listed in the 1998 report (M. Wang, personal communication, January 13, 2015).

In addition to the 1998 AA report, there were a few other studies which provide LCI data for aluminum shape casting. The DOE examined the energy and environmental profile of the metal casting industry in the U.S. in 1999. Stephens et al specifically investigated the aluminum casting processes including lost foam, semi-permanent and precision sand in 2001. They obtained material and energy flow data from six aluminum foundries in the U.S. and calculated the environmental footprint of cast aluminum. Dalquist and Gutowski published another study in 2004, exclusively focusing on die casting. The study by Stephens et al seemed the most appropriate to be included in the GREET update. Unfortunately, the energy consumption data they reported included the upstream energy associated with fuel production and electricity generation, which makes it difficult to separate it from the process energy use. The energy consumption data found in these studies is summarized in Table 7.

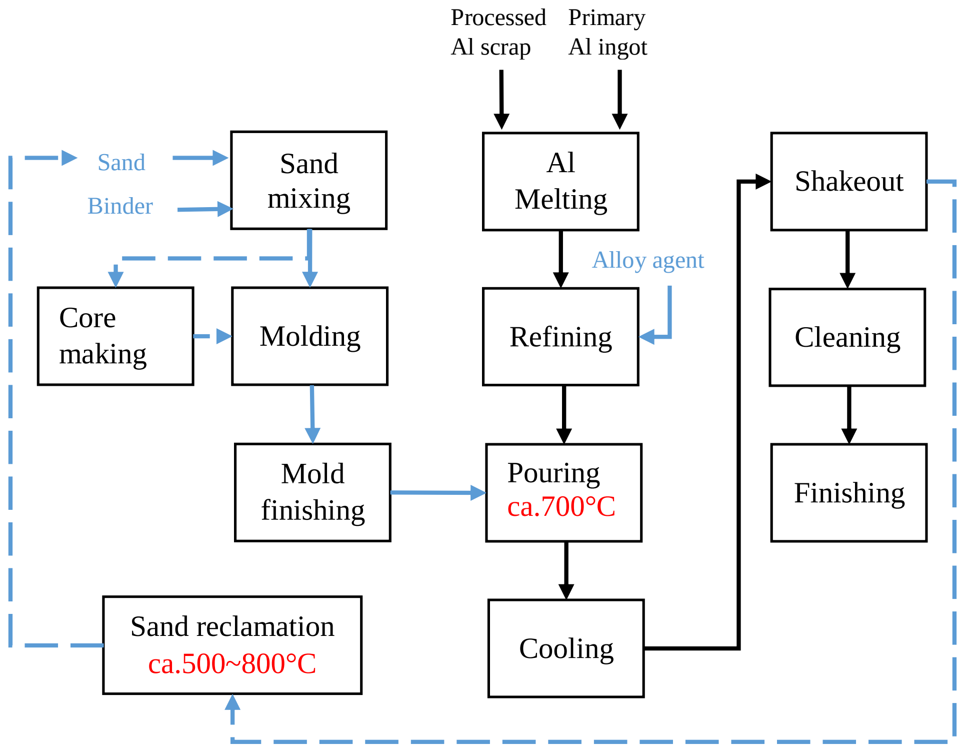

FIGURE 3 Process flow diagram for aluminum casting. Black lines represent the flows of aluminum. Blue lines represent the flows of materials other than aluminum. Dashed lines represent recycling practices.

It can be observed from Table 7 that the energy consumption of aluminum casting can be greatly reduced if a foundry receives aluminum in molten form, as it eliminated the need for remelting. In fact, shipping molten aluminum is a common practice within the aluminum industry. Molten aluminum is stored in ladles made of refractory material and can be delivered over a distance up to 200 km (Braulio *et al*, 2014). To prepare for the shipping, the ladle needs to be preheated to 800°C to prevent thermal shock damage resulting from contact with molten aluminum. Also, the molten aluminum needs to be overheated by 100°C to offset the heat loss during delivery (Bonadia *et al* 2006). Based on our thermodynamic calculation, the additional energy consumption for preheating the ladle, overheating the aluminum and hauling the deadweight (~50%) of the ladle is estimated to be around 1.0 MMBtu per ton of molten aluminum delivered. Compared with the energy consumption of 2.5 MMBtu/ton aluminum for aluminum melting, a savings of 1.5 MMBtu/ton aluminum can be achieved with molten aluminum delivery. This could partially explain the variation in energy requirements for aluminum shape casting reported in different literature. Energy consumption also varies considerably with the choice of casting technologies. Due to the variation, and lack of information on the portion of aluminum delivered in molten form, no change was made to the shape casting LCI in the 2014 GREET model.

TABLE 7 Energy consumption for shape casting (MMBtu/short ton)

		Sand casting	Lost foam casting	Die casting	Semi-permanent molding	Precision sand casting
Metal melting		2.5-5.0	2.5-5.0	2.5-5.0; 2.53[b]	2.5-5.0	2.5-5.0
Casting	Core/mold making	1.0-3.0	---	---	---	---
	Pouring and cooling	0.6	---	---	---	---
	Sand reclamation	0.5 (optional)	---	---	---	---
	Total	1.6-4.1	2.5	4.4-5.2; 2.71[b]	---	---
Cleaning and finishing		1	1	1	1	1
Total (molten Al)		2.6-5.1	3.5; 19.6[a]	5.4-6.2; 3.71[b]	24.5[a]	32.2[a]
Total (Al ingot)		5.1-10.1	5.5-8.5	7.9-11.2; 6.24[b]	---	---

[a] Stephens et al, 2001. Note that these included upstream energy.

[b] Dalquist and Gutowski, 2004

The rest of the data are from DOE, 1999.

It should be pointed out that the LCI for aluminum shape casting in the 2014 GREET model does not contain emission data for criteria air pollutants. Aluminum shape casting gives off significant amounts of PM emissions from pouring, shakeout, grinding, milling and sand reclamation processes. Vaporization, thermal decomposition and combustion of organic chemical binders and lubricants also emit considerable amounts of PM, VOCs, NO_x and SO_x (DOE, 1999). The 1998 AA report did list air emissions in the input-output table for aluminum shape casting. However, these numbers seemed abnormally high and therefore were not used in GREET. This data gap should be addressed when reliable air emission data becomes available.

3 RESULTS AND DISCUSSION

This report compiled LCI tables for the processes pertaining to primary aluminum production, secondary aluminum production and aluminum semi-fabrication based on the most recent data representing the industrial averages in North America, except for bauxite mining, bauxite refining and anode production, which were based on global averages. The LCI tables to be incorporated into GREET are listed in Appendix B. Detailed combustion emissions estimated using GREET, and the calculated process emissions are also provided in Appendix B. Compared with the LCIs in the 2014 GREET model, energy consumption data representative of 2006 production was replaced with data for 2010, and process emission data was either added or updated for most of the processes. In addition to the energy and material inputs, and criteria air pollutant emissions, fluorides (HF, NaF and AlF_3) and chlorides (HCl, NaCl, $MgCl_2$, $AlCl_3$) emissions associated with aluminum production reported in AA 2013 are summarized in Table 8, as they are regulated by EPA and are a concern of aluminum producers (EPA 2014b, EPA 2012). This effort to update the aluminum LCIs in the 2014 GREET model, however, does not address all issues and has its own limitations.

TABLE 8 Fluorides and chlorides emissions for aluminum production (gram/short ton)

	Anode production	Alumina reduction	Primary ingot casting	Secondary ingot casting	Hot rolling
Fluorides	3.85	925	---	23.4	0.998
Chlorides	---	---	22.2	82.1	52.7

The updated LCIs do not include all material inputs and outputs associated with semi-fabricated aluminum manufacturing. The exclusion of refractory materials, inert gases, lubricants, solvent, paint, filter media, chemicals including aluminum fluoride, sulfuric acid, chlorine and its derivatives, as well as packaging materials such as paper, wood and plastic, is not expected to impact the results in any noticeable way, since the consumed quantities are quite small (<<1% of the total material inputs). Infrastructure and machinery needed for aluminum production are not included either in the absence of reliable data. One noteworthy piece of infrastructure is the potliner, which is comprised of a carbon inner lining, a refractory brick outer lining and a steel shell, and typically has a service life of 4 to 7 years (EPA 2000). Nonetheless, the spent potliner generation rate was estimated to be 0.02 ton/ton of produced aluminum in 1997 (EPA 2000). The potliner therefore should not exert discernable influences on the results.

Water consumption calculated as the differences between water withdrawals and wastewater discharges provided in the 2013 AA report, are included in the LCIs for each production stage. Consumption can be as high as over one thousand gallons per ton of product for a unit process. However, caution should be exercised when interpreting the water footprint data. Firstly, it is not clear how much of the consumed water reported in AA 2013 was used as cooling water for on-site electricity generation. GREET already accounts for water consumption for fuel production and electricity generation, so including the reported water consumption without taking out the portion used for cooling would lead to a double counting problem. Secondly, consumption of process water, especially water used for pollution control, is highly dependent on location, because water availability dictates treatment technologies (European Aluminum Association, 2013). For example, a facility in the coastal region would opt for wet scrubbing as the stack gas treatment technology and consequently consume large amounts of sea water, whereas a facility without easy access to water would have to use dry scrubbing. Since water consumption varies substantially with the choice of pollution control technologies, and sites with different pollution control technologies are systems consisting of different processes, the average for the sites may not represent the industrial norm. Therefore, the water consumption reported in AA 2013 may not be a good representation of the industrial average.

For materials that are included in the LCIs, there are a few cases where assumptions were made for the material production due to data unavailability. All alloy agents used in aluminum production were assumed to be primary aluminum in this study. Although the content of alloying materials is usually low (<2%), the most common alloy agents used are copper, magnesium, silicon and zinc, which have different environmental profiles than aluminum. This should be revisited when more information on the composition of aluminum alloys becomes available. For anode production, the coal pitch used was assumed to be coke produced from coal by the coke oven for steel production, due to limited data on pitch production in GREET. Although pitch production is similar to that of coke, it gives off toxic coal tar pitch volatiles (Blümer, 2000), which are regulated by the U.S. Occupational Safety and Health Administration. Therefore, this approximation should be fixed when pitch data in GREET is updated.

This update also does not cover all processes associated with aluminum production. Excluded processes worth mentioning include recycling of red mud, and recycling of dross and salt cake. The aluminum industry has long been trying to recycle these materials, since their disposal has caused various environmental problems. In AA 2013, the material and energy flow for dross and salt cake recycling is reported. Nonetheless, it is not stated clearly in the report how concentrated dross and salt cake were produced from collected waste. Therefore, that LCI is not included in this update.

APPENDIX A
CALCULATION OF THE ELECTRICITY MIX REPRESENTING U.S. CONSUMPTION OF PRIMARY AL

To better represent the sources of electricity for the smelting of primary aluminum used in the U.S., an electricity mix was calculated based on primary aluminum flows pertinent to the U.S. aluminum market and their corresponding electricity sources. Primary aluminum flows of interest include domestically supplied aluminum and imported aluminum. It was assumed that all imported aluminum is used in the U.S. without being re-exported to another country, so the U.S. self-supplied aluminum is equal to the difference between domestically produced aluminum and exported aluminum. The primary aluminum used in the U.S., therefore, can be calculated by Equation [1].

$$Al_{Market} = Al_{dp} - Al_{exp} + \sum_i Al_{imp,i} \qquad [1]$$

Where Al_{dp} represents aluminum produced in the U.S., Al_{exp} represents aluminum exported by the U.S., and $Al_{imp,\,i}$ represents aluminum imported by the U.S. from country i.

U.S. data for domestic production, import and export of aluminum were obtained from USGS (USGS 2013, USGS 2010). It should be noted that USGS provides import and export data for crude (ingot, pig, slab, etc.) aluminum, semicrude (semi-fabricated) aluminum and aluminum scrap. As aluminum scrap is not relevant to primary aluminum production, only crude and semicrude aluminum flows were considered in this analysis. The electricity mix for aluminum used in the U.S. was then calculated as a weighted average, with the quantity of aluminum from each country assigned as the weight, as shown in Equation [2]. A country-specific electricity mix for aluminum smelting, obtained from IAI (IAI 2015a), was applied to the aluminum flow for the corresponding country. For countries whose aluminum smelting electricity mix was not found (Russia, UAE, Argentina, Germany and Venezuela), their national electricity mix obtained from the International Energy Agency (IEA) was used instead (IEA 2015). For countries whose aluminum export to the U.S. is less than 2% of the total import by the U.S., the world-average electricity mix for aluminum smelting reported by IAI was applied (IAI 2015a).

$$Elec_{Market,j} = \frac{(Al_{dp} - Al_{exp}) \times Elec_{U.S.,j} + \sum_i Al_{imp,i} \times Elec_{i,j}}{\sum_j \left((Al_{dp} - Al_{exp}) \times Elec_{U.S.,j} + \sum_i Al_{imp,i} \times Elec_{i,j} \right)} \qquad [2]$$

Where $Elec_{U.S.,\,j}$ represents the percentage of U.S. aluminum smelting electricity from source j, and $Elec_{i,\,j}$ represents the percentage of aluminum smelting electricity from source j in country i.

The weighted average electricity mixes for aluminum used in the U.S. based on data for 2010 and 2013 are summarized in Table A-1 and Table A-2.

TABLE A-1 2010 electricity mix for aluminum used in the U.S.

	U.S.	Canada	China	Russia	Germany	Argentina	UAE	Venezuela	World	Weighted avg.
Hydro	32.2%	100.0%	10.0%	16.2%	4.3%	27.0%	0.0%	64.9%	41.4%	66.6%
Coal	65.2%	0.0%	90.0%	16.0%	43.2%	2.2%	0.0%	0.0%	51.4%	22.5%
Oil	0.0%	0.0%	0.0%	0.9%	1.4%	13.3%	1.5%	15.2%	0.1%	1.0%
NG	1.3%	0.0%	0.0%	50.1%	14.3%	50.0%	98.5%	19.9%	5.0%	7.7%
Nuclear	1.3%	0.0%	0.0%	16.4%	22.2%	5.7%	0.0%	0.0%	2.1%	1.8%
Other	0.0%	0.0%	0.0%	0.4%	14.6%	1.8%	0.0%	0.0%	0.0%	0.3%
Production shares	14.2%	53.0%	6.5%	5.2%	1.6%	3.3%	1.9%	3.0%	11.3%	---

TABLE A-2 2013 electricity mix for aluminum used in the U.S.

	U.S.	Canada	China	Russia	Germany	Argentina	UAE	World	Weighted avg.
Hydro	52.3%	100.0%	10.0%	15.6%	4.4%	22.0%	0.0%	36.1%	69.7%
Coal	35.9%	0.0%	90.0%	15.8%	45.6%	2.7%	0.0%	54.1%	16.8%
Oil	0.0%	0.0%	0.0%	2.6%	1.2%	14.8%	0.0%	0.1%	0.5%
NG	10.4%	0.0%	0.0%	49.1%	12.3%	53.7%	100.0%	8.3%	11.2%
Nuclear	1.4%	0.0%	0.0%	16.6%	15.8%	4.7%	0.0%	1.4%	1.5%
Other	0.0%	0.0%	0.0%	0.3%	20.7%	2.1%	0.0%	0.0%	0.4%
Production share	9.3%	57.9%	4.5%	4.5%	1.8%	2.1%	5.5%	14.5%	---

Considering that the U.S. is one of the major producers of secondary aluminum, among other countries which the U.S. imports considerable amounts of aluminum from, such as China, Russia, and Germany, it is likely that the crude and semicrude aluminum flows in the U.S. market contain a mixture of primary and secondary aluminum. To address this concern, the ratio of primary aluminum production to the combined production of primary and secondary aluminum was calculated and applied to the aluminum flows for these countries. Primary aluminum production data were obtained from USGS (USGS 2013, USGS 2010), except for the data of China, which were from IAI (IAI 2015b). Secondary aluminum production data for the U.S., Canada, and Germany were acquired from USGS (USGS 2014, USGS 2013, USGS 2010, Menzie *et al* 2010). Data for China were excerpted from China Nonferrous Metals Industry Statistical Yearbook 2014 (China Nonferrous Metals Industry Association 2015), and data for Russia were obtained from IAI (IAI 2015b). The electricity mix for aluminum used in the U.S., taking into account the mixed flow of primary and secondary aluminum, can be calculated by Equation [3].

$$Elec'_{Market,j} = \frac{(Al_{dp} - Al_{exp} \times f_{u.s.}) \times Elec_{U.S.,j} + \sum_i Al_{imp,i} \times f_i \times Elec_{i,j}}{\sum_j\left((Al_{dp} - Al_{exp} \times f_{u.s.}) \times Elec_{U.S.,j} + \sum_i Al_{imp,i} \times f_i \times Elec_{i,j}\right)} \qquad [3]$$

Where $f_{U.S.}$ represents the share of primary aluminum production in the U.S., and f_i represents the share in country i. The adjusted electricity mixes for U.S. market aluminum in 2010 and 2013 are shown in Table A-3 and A-4.

For comparison purposes, the electricity mixes for North American smelters as reported by IAI (IAI 2015a), are provided in Table A-5.

TABLE A-3 2010 electricity mix for aluminum used in the U.S., considering mixed flow of primary and secondary aluminum

	U.S.	Canada	China	Russia	Germany	Argentina	UAE	Venezuela	World	Weighted avg.
Hydro	32.2%	100.0%	10.0%	16.2%	4.3%	27.0%	0.0%	64.9%	41.4%	62.8%
Coal	65.2%	0.0%	90.0%	16.0%	43.2%	2.2%	0.0%	0.0%	51.4%	27.9%
Oil	0.0%	0.0%	0.0%	0.9%	1.4%	13.3%	1.5%	15.2%	0.1%	0.9%
NG	1.3%	0.0%	0.0%	50.1%	14.3%	50.0%	98.5%	19.9%	5.0%	6.7%
Nuclear	1.3%	0.0%	0.0%	16.4%	22.2%	5.7%	0.0%	0.0%	2.1%	1.5%
Other	0.0%	0.0%	0.0%	0.4%	14.6%	1.8%	0.0%	0.0%	0.0%	0.2%
Primary prod shares	27.0%	46.3%	4.7%	4.2%	0.6%	2.9%	1.7%	2.6%	10.0%	---

TABLE A-4 2013 electricity mix for aluminum used in the U.S., considering mixed flow of primary and secondary aluminum

	U.S.	Canada	China	Russia	Germany	Argentina	UAE	World	Weighted avg.
Hydro	52.3%	100.0%	10.0%	15.6%	4.4%	22.0%	0.0%	36.1%	67.5%
Coal	35.9%	0.0%	90.0%	15.8%	45.6%	2.7%	0.0%	54.1%	19.5%
Oil	0.0%	0.0%	0.0%	2.6%	1.2%	14.8%	0.0%	0.1%	0.4%
NG	10.4%	0.0%	0.0%	49.1%	12.3%	53.7%	100.0%	8.3%	11.2%
Nuclear	1.4%	0.0%	0.0%	16.6%	15.8%	4.7%	0.0%	1.4%	1.3%
Other	0.0%	0.0%	0.0%	0.3%	20.7%	2.1%	0.0%	0.0%	0.2%
Production share	25.6%	48.4%	3.1%	3.7%	0.6%	1.8%	4.6%	12.3%	---

TABLE A-5 Electricity mix for aluminum smelting in North America

	Hydro	Coal	Oil	Natural gas	Nuclear
2010	75.1%	24.0%	0.0%	0.5%	0.5%
2013	81.1%	14.2%	0.0%	4.1%	0.5%

APPENDIX B
LCI TABLES FOR ALUMINUM PRODUCTION

TABLE B-1 LCI of bauxite mining, normalized to 1 ton of primary aluminum produced

	Quantity	Unit
Fuel inputs		
Resid. oil	0.213	MMBtu
Diesel	0.348	MMBtu
Gasoline		MMBtu
Natural gas		MMBtu
Coal		MMBtu
Liquefied petroleum gas		MMBtu
Electricity	0.016	MMBtu
Total	0.577	MMBtu
Material inputs		
Sodium Hydroxide (50%)		ton
Lime		ton
Coke		ton
Steel Sheet Part		ton
Water consumption	1,485.663	gal
Non-combustion Emissions		
VOC		g
CO		g
NOx		g
PM10	852.218	g
PM2.5	429.879	g
SOx		g
CH4		g
N2O		g
CF4		g
C2F6		g
CO2		g

Note: to convert the inventory to represent the production of 1 ton of Al_2O_3, divide by 1.935, as the production of 1 kg of primary aluminum requires the input of 1.935 kg Al_2O_3 (AA 2013).

TABLE B-2 LCI of bauxite refining, normalized to 1 ton of primary aluminum produced

	Quantity	Unit
Fuel inputs		
Resid. oil	2.948	MMBtu
Diesel	0.003	MMBtu
Gasoline		MMBtu
Natural gas	12.908	MMBtu
Coal	1.340	MMBtu
Liquefied petroleum gas		MMBtu
Electricity	0.636	MMBtu
Total	17.835	MMBtu
Material inputs		
Sodium Hydroxide (50%)	0.306	ton
Lime	0.078	ton
Coke		ton
Steel Sheet Part		ton
Water consumption	823.598	gal
Non-combustion Emissions		
VOC		g
CO		g
NOx	19.726	g
PM10	790.785	g
PM2.5	365.759	g
SOx	1,465.616	g
CH4		g
N2O		g
CF4		g
C2F6		g
CO2		g

Note: to convert the inventory to represent the production of 1 ton of Al_2O_3, divide by 1.935, as the production of 1 kg of primary aluminum requires the input of 1.935 kg Al_2O_3 (AA 2013).

TABLE B-3 LCI of anode production, normalized to 1 ton of primary aluminum produced

	Quantity	Unit
Fuel inputs		
Resid. oil	0.521	MMBtu
Diesel	0.095	MMBtu
Gasoline		MMBtu
Natural gas	0.706	MMBtu
Coal		MMBtu
Liquefied petroleum gas		MMBtu
Electricity	0.165	MMBtu
Total	1.486	MMBtu
Material inputs		
Sodium Hydroxide (50%)		ton
Lime		ton
Coke	0.349	ton
Steel Sheet Part	0.003	ton
Water consumption	11.299	gal
Non-combustion Emissions		
VOC		g
CO		g
NOx	120.638	g
PM10	72.041	g
PM2.5	35.564	g
SOx	829.749	g
CH4		g
N2O		g
CF4		g
C2F6		g
CO2	41,915.434	g

TABLE B-4 LCI of alumina reduction, for 1 ton of primary aluminum produced

	Quantity	Unit
Fuel inputs		
Resid. oil		MMBtu
Diesel		MMBtu
Gasoline		MMBtu
Natural gas		MMBtu
Coal		MMBtu
Liquefied petroleum gas		MMBtu
Electricity	46.778	MMBtu
Total	46.778	MMBtu
Material inputs		
Sodium Hydroxide (50%)		ton
Lime		ton
Coke	0.006	ton
Steel Sheet Part	0.004	ton
Water consumption	57.518	gal
Non-combustion Emissions		
VOC		g
CO		g
NOx	235.872	g
PM10	1,759.968	g
PM2.5	879.984	g
SOx	13,862.016	g
CH4		g
N2O		g
CF4	69.764	g
C2F6	9.616	g
CO2	1,391,644.800	g

TABLE B-5 LCI of primary ingot casting, for 1 ton of primary ingot produced

	Quantity	Unit
Fuel inputs		
Resid. oil	0.106	MMBtu
Diesel	0.029	MMBtu
Gasoline		MMBtu
Natural gas	0.659	MMBtu
Coal		MMBtu
Liquefied petroleum gas	0.003	MMBtu
Electricity	0.209	MMBtu
Total	1.006	MMBtu
Material inputs		
Sodium Hydroxide (50%)		ton
Lime		ton
Coke		ton
Steel Sheet Part		ton
Water consumption	55.121	gal
Non-combustion Emissions		
VOC		g
CO		g
NOx	26.644	g
PM10	27.511	g
PM2.5	12.753	g
SOx	27.423	g
CH4		g
N2O		g
CF4		g
C2F6		g
CO2		g

TABLE B-6 LCI of scrap preparation, normalized to 1 ton of secondary ingot produced

	Quantity	Unit
Fuel inputs		
Resid. oil		MMBtu
Diesel		MMBtu
Gasoline		MMBtu
Natural gas	0.746	MMBtu
Coal		MMBtu
Liquefied petroleum gas		MMBtu
Electricity	0.345	MMBtu
Total	1.092	MMBtu
Material inputs		
Sodium Hydroxide (50%)		ton
Lime	0.001	ton
Coke		ton
Steel Sheet Part		ton
Water consumption	0.105	gal
Non-combustion Emissions		
VOC		g
CO		g
NOx		g
PM10		g
PM2.5		g
SOx		g
CH4		g
N2O		g
CF4		g
C2F6		g
CO2		g

TABLE B-7 LCI of secondary ingot casting, for 1 ton of secondary ingot produced

	Quantity	Unit
Fuel inputs		
Resid. oil		MMBtu
Diesel		MMBtu
Gasoline		MMBtu
Natural gas	4.118	MMBtu
Coal		MMBtu
Liquefied petroleum gas		MMBtu
Electricity	0.342	MMBtu
Total	4.460	MMBtu
Material inputs		
Sodium Hydroxide (50%)		ton
Lime	0.004	ton
Coke		ton
Steel Sheet Part		ton
Primary Al Ingot	0.08	ton
Water consumption	73.148	gal
Non-combustion Emissions		
VOC	69.554	g
CO		g
NOx	42.751	g
PM10	242.203	g
PM2.5	113.880	g
SOx	20.458	g
CH4	0.354	g
N2O	0.336	g
CF4		g
C2F6		g
CO2	6.613	g

TABLE B-8 LCI of extrusion, for 1 ton of extruded aluminum

	Quantity	Unit
Fuel inputs		
Resid. oil		MMBtu
Diesel		MMBtu
Gasoline		MMBtu
Natural gas	5.288	MMBtu
Coal		MMBtu
Liquefied petroleum gas		MMBtu
Electricity	0.610	MMBtu
Total	5.897	MMBtu
Material inputs		
Sodium Hydroxide (50%)	0.008	ton
Lime		ton
Coke		ton
Steel Sheet Part	0.001	ton
Water consumption	105.308	gal
Non-combustion Emissions		
VOC	243.397	g
CO		g
NOx	0.000	g
PM10		g
PM2.5		g
SOx	5.021	g
CH4		g
N2O		g
CF4		g
C2F6		g
CO2		g

TABLE B-9 LCI of hot rolling, for 1 ton of hot-rolled aluminum

	Quantity	Unit
Fuel inputs		
Resid. oil		MMBtu
Diesel		MMBtu
Gasoline		MMBtu
Natural gas	3.278	MMBtu
Coal		MMBtu
Liquefied petroleum gas		MMBtu
Electricity	0.351	MMBtu
Total	3.629	MMBtu
Material inputs		
Sodium Hydroxide (50%)		ton
Lime		ton
Coke		ton
Steel Sheet Part		ton
Water consumption	19.670	gal
Non-combustion Emissions		
VOC	256.394	g
CO		g
NOx	85.881	g
PM10	98.819	g
PM2.5	43.661	g
SOx	6.559	g
CH4		g
N2O		g
CF4		g
C2F6		g
CO2		g

TABLE B-10 LCI of cold rolling, for 1 ton of cold-rolled aluminum

	Quantity	Unit
Fuel inputs		
Resid. oil		MMBtu
Diesel		MMBtu
Gasoline		MMBtu
Natural gas	1.888	MMBtu
Coal		MMBtu
Liquefied petroleum gas		MMBtu
Electricity	1.134	MMBtu
Total	3.022	MMBtu
Material inputs		
Sodium Hydroxide (50%)		ton
Lime		ton
Coke		ton
Steel Sheet Part		ton
Water consumption	65.284	gal
Non-combustion Emissions		
VOC	235.430	g
CO	3.720	g
NOx	0.000	g
PM10	53.525	g
PM2.5	23.451	g
SOx	0.000	g
CH4	1.089	g
N2O	0.998	g
CF4		g
C2F6		g
CO2		g

TABLE B-11 Reported emission, GREET estimated combustion emission and estimated process emission for 1 short ton of primary aluminum

	Bauxite mining			Alumina refining			Anode production			Electrolysis			Primary ingot casting		
	AA 2013	GREET est.	Est. process	AA 2013	GREET est.	Est. process	AA 2013	GREET est.	Est. process	AA 2013	GREET est.	Est. process	AA 2013	GREET est.	Est. process
VOC	N/A	0.3	N/A	N/A	37.1	N/A	N/A	2.3	N/A	N/A	0.0	N/A	N/A	1.8	N/A
NO_x	N/A	30.9	N/A	1,194	1,174	19.7	217.7	97.6	120.2	235.9	0.0	235.9	65.3	38.8	26.5
PM_{10}	859.8	7.6	852.2	983	192.3	790.8	92.9	20.9	72.0	1,760	0.0	1,760	33.6	6.1	27.5
$PM_{2.5}$	429.9	5.5	424.4	491.5	125.8	365.8	46.5	10.9	35.6	880	0.0	880	16.8	4.0	12.8
SO_x	N/A	145.8	N/A	4,213	2,747	1,466	1,186	356.2	829.7	13,862	0.0	13,862	99.8	72.4	27.4

TABLE B-12 Reported emission, GREET estimated combustion emission and estimated process emission for 1 short ton of secondary aluminum and aluminum semi-products

	Secondary ingot casting			Hot rolling			Cold rolling			Extrusion		
	AA 2013	GREET est.	Est. process	AA 2013	GREET est.	Est. process	AA 2013	GREET est.	Est. process	AA 2013	GREET est.	Est. process
VOC	80.0	10.5	69.6	264.7	8.3	256.4	240.2	4.8	235.4	256.8	13.4	243.4
NO_x	192.7	149.9	42.8	205.2	119.3	85.9	55.3	68.7	-13.4	142.4	192.5	-50.0
PM_{10}	256.6	14.4	242.2	110.3	11.5	98.8	60.1	6.6	53.5	N/A	18.5	N/A
$PM_{2.5}$	128.3	14.4	113.9	55.2	11.5	43.7	30.1	6.6	23.5	N/A	18.5	N/A
SO_x	21.6	1.1	20.5	7.4	0.9	6.6	0.3	0.5	-0.2	6.4	1.4	5.0

REFERENCES

Blümer, G.P., Collin, G., Höke, H., 2000. Tar and Pitch, in: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA.

Bonadia, P. *et al*. 2006. Refractory selection for long-distance molten-aluminum delivery. *Am. Ceram. Soc. Bull.*, 85(8), 9301-9309.

Braulio, M.A. *et al*. 2014. Molten aluminum long-distance transportation: a refractory issue. Chapter 214 in *Proceedings of the unified international technical conference on refractories (UNITECR 2013)*. Hoboken, NJ: John Wiley & Sons, Inc.

Burnham, A. *et al*. 2006. Development and applications of GREET 2.7-the transportation vehicle-cycle model. ANL/ESD/06-5.

China Nonferrous Metals Industry Association. 2015. China Nonferrous Metal Industry Statistical Yearbook 2014.

Colett, J.S., Kelly, J.C., Keoleian, G.A., 2015. Using Nested Average Electricity Allocation Protocols to Characterize Electrical Grids in Life Cycle Assessment: A Case Study of U.S. Primary Aluminum Production. *J. Ind. Ecol.* doi:10.1111/jiec.12268

Cullen, J.M. and Allwood, J.M. 2013. Mapping the global flow of aluminum: from liquid aluminum to end-use goods. *Environ. Sci. Technol.*, 47, 3057-3064.

Dalquist, S. and Gutowski, T. 2004. Life cycle analysis of conventional manufacturing techniques: die casting. http://web.mit.edu/ebm/Publications/Die%20Casting%20 Dalquist%20Gutowski.pdf

European Aluminum Association. 2013. Environmental profile report for the European aluminum industry. http://www.alueurope.eu/wp-content/uploads/2011/10/ Environmental-Profile-Report-for-the-European-Aluminium-Industry-April-2013.pdf

Green, J.A.S., 2007. Aluminum Recycling and Processing for Energy Conservation and Sustainability. ASM International.

The International Aluminum Institute. 2015a. Primary Aluminum Smelting Power Consumption Statistics. http://www.world-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/

The International Aluminum Institute. 2015b. Global Mass Flow Model 2013. http://www.world-aluminium.org/media/filer_public/2015/04/23/2013_2014draft.xlsx

The International Energy Agency. 2015. Statistics for electricity and heat. http://www.iea.org/statistics/statisticssearch/

Keoleian, G. *et al*. 2012. Life cycle material data update for GREET model. https://greet.es.anl.gov/files/greet2-lca-update

Nappi, C. 2013. The global aluminum industry 40 years from 1972. http://www.world-aluminium.org/media/filer_public/2013/02/25/an_outlook_of_the_global_aluminium_industry_1972_-_present_day.pdf

PE Americas. 2010. Life cycle impact assessment of aluminum beverage cans. http://www.container-recycling.org/assets/pdfs/aluminum/LCA-2010-AluminumAssoc.pdf

Reck, B.K., Graedel, T.E., 2012. Challenges in Metal Recycling. Science 337, 690–695. doi:10.1126/science.1217501

Sleppy, W.C., 2000. Aluminum Compounds, Introduction, in: Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc.

Statistics Canada, 2014. Report on Energy Supply and Demand in Canada 2011 version. http://www.statcan.gc.ca/pub/57-003-x/2014001/tablesectlist-listetableauxsect-eng.htm

Stephens, R. *et al*. 2001. Life cycle assessment of aluminum casting processes. SAE Technical Paper 2001-01-3726.

The Aluminum Association. 2013. The Environmental footprint of semi-finished aluminum products in North America. http://www.aluminum.org/sites/default/files/LCA_Report_Aluminum_Association_12_13.pdf

The Aluminum Association. 2008. Rolling aluminum: from the mine through the mill. http://www.aluminum.org/sites/default/files/Rolling_Aluminum_From_The_Mine_Through_The_Mill.pdf

The Aluminum Association. 1998. Life cycle inventory report for the North American aluminum industry.

U.S. Department of Energy. 1999. Energy and environmental profile of the U.S. metalcasting industry. http://energy.gov/sites/prod/files/2013/11/f4/profile_0.pdf

U.S. Department of Energy. 1998. Total energy cycle assessment of electric and conventional vehicles: an energy and environmental analysis. ANL/ES/RP—96387.

U.S. Environmental Protection Agency. 2014a. eGRID ninth edition with year 2010 data. http://www.epa.gov/cleanenergy/energy-resources/egrid/

U.S. Environmental Protection Agency. 2014b. National emission standards for hazardous air pollutants for primary aluminum reduction plants (proposed). http://www.gpo.gov/fdsys/pkg/FR-2014-12-08/pdf/2014-27499.pdf

U.S. Environmental Protection Agency. 2012. National emission standards for hazardous air pollutants: secondary aluminum production (proposed). http://www.epa.gov/ttn/atw/alum2nd/fr14fe12.pdf

U.S. Environmental Protection Agency. 2000. Best demonstrated available technology: background document for spent aluminum potliners – K088. http://www.epa.gov/wastes/hazard/tsd/ldr/k088/k088back.pdf

U.S. Geological Survey. 2015a. Mineral Commodity Summaries: Aluminum. http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/mcs-2015-alumi.pdf

U.S. Geological Survey. 2015b. Mineral Commodity Summaries: Bauxite and Alumina. http://minerals.usgs.gov/minerals/pubs/commodity/bauxite/mcs-2015-bauxi.pdf

U.S. Geological Survey. 2014. 2012 Minerals Yearbook Canada. http://minerals.usgs.gov/minerals/pubs/country/2012/myb3-2012-ca.pdf

U.S. Geological Survey. 2013. Minerals Yearbook: Aluminum. http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/myb1-2013-alumi.pdf

U.S. Geological Survey. 2010. Minerals Yearbook: Aluminum. http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/myb1-2010-alumi.pdf

Wang, M. 2015. Personal communication (February 13, 2015).

Argonne
NATIONAL LABORATORY

Energy Systems Division
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4854

www.anl.gov

U.S. DEPARTMENT OF
ENERGY