Life Cycle Assessment of North American Aluminum Cans

On behalf of The Aluminum Association

Client:	The Aluminum Association
Title:	Life Cycle Assessment of North American Aluminum Cans
Report version:	v1.0
Report date:	May 19, 2021

On behalf of Sphera Solutions, Inc. and its subsidiaries

Document prepared by

Manuela Toro

05/19/2021

Vicki Rybl

Quality assurance by

Christoph Koffler
Technical Director Americas
05/19/2021
ckoffler@sphera.com
Phone+1 617 247 4477

Under the supervision of

Maggie Wildnauer

Consulting Director Americas

Table of Contents

List of Figures

List of Tables

List of Acronyms

AA	Aluminum Association
ADP	Abiotic Depletion Potential
AP	Acidification Potential
CA	Canada
CN	China
EoL	End-of-Life
EP	Eutrophication Potential
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NCV	Net Calorific Value (a.k.a. Lower Heating Value, LHV)
NMVOC	Non-Methane Volatile Organic Compound
ODP	Ozone Depletion Potential
PED	Primary Energy Demand
RME	Regional Middle East
RNA	Regional North America
SETAC	Society of Environmental Toxicology And Chemistry
SFP	Smog Formation Potential
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UBC	Used Beverage Can
VOC	Volatile Organic Compound
WHO	World Health Organization

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).

Executive Summary

This report documents the average life cycle inventory (LCI) and life cycle impact assessment (LCIA) results of 1,000 aluminum beverage cans manufactured in North America (U.S. and Canada) in the reference year 2016. The study was commissioned by the Aluminum Association (AA) to update a previous study published in 2014 to respond to increasing market demand for up-to-date life cycle data on the environmental performance of products. The goal of this study is to provide current life cycle inventory data for beverage cans to help the aluminum industry and its stakeholders, life cycle assessment practitioners, academic researchers and other interested parties better understand the potential environmental impacts of aluminum cans and their improvement over time.

A life cycle inventory of a product quantifies all material and energy use and environmental exchanges (resources, emissions) over its entire life cycle from raw material acquisition through to recycling and/or disposal. The functional unit of the study is 1,000 unfilled aluminum cans with a weighted average size of 13.6 oz. beverage volume per can. This average represents a basket of small, medium, and large sized cans, represented by their relative market shares. The scope of the study is "cradle-to-grave", i.e., starting with the extraction of bauxite ore and ending with the recycling and recovery of used beverage cans (UBCs). Beverage filling, distribution, refrigeration, and consumption are excluded from this study.

In addition, "cradle-to-gate" results are provided for users who prefer to assess the environmental footprint of the cans from a different perspective or using an alternative allocation approach. "Cradle-to-gate" refers to the stages of the life cycle starting with raw material extraction and ending with a finished can at the manufacturing facility.

Both approaches used primary production data for the reference year 2016 to assess the same baseline scenario:

- A total metallic weight of 12.99 kg per 1,000 cans with an average size of 13.6 oz per can;
- An end-of-life (EoL) recycling rate of 50.4%;
- A recycled metal content of 73% per can including 50% from post-consumer sources and 23% from pre-consumer sources, but excluding internal scrap from can sheet rolling mills; and
- No embedded burden of primary aluminum production assigned to any scrap inputs.

Focusing on two frequently cited assessment parameters – Primary Energy Demand (PED) and Global Warming Potential (GWP, commonly called carbon footprint) – the study has reached the following conclusions:

- The **cradle-to-gate** PED and GWP for 1,000 cans, from raw material extraction to the point in which an empty beverage can is made, painted and sealed, are 1,320 MJ LHV and 77.1 kg CO_2 equivalents, respectively.
- The **cradle-to-grave** PED and GWP for 1,000 cans, including end-of-life disposal and recycling, are 1,630 MJ LHV and 96.8 kg CO_2 equivalents, respectively.

Notably, the cradle-to-gate footprint is lower than the cradle-to-grave footprint. This is unusual for products that are fully recycled at the end of their useful life and receive a credit of primary production based on the amount of the recovered secondary material. In the specific case of aluminum cans made in North America, however, the EoL recycling rate is lower than the recycled content. Collecting less aluminum scrap in end-of-life recycling than what is consumed during production leads to a *net scrap deficit* of the product system, which burdens the product system and increases the PED and GWP of the beverage can over the full life cycle. Bringing back more aluminum cans through increased consumer recycling is therefore one of the key opportunities to reduce the cradle-to-grave environmental footprint of aluminum beverage cans in the future (Figure ES-1).

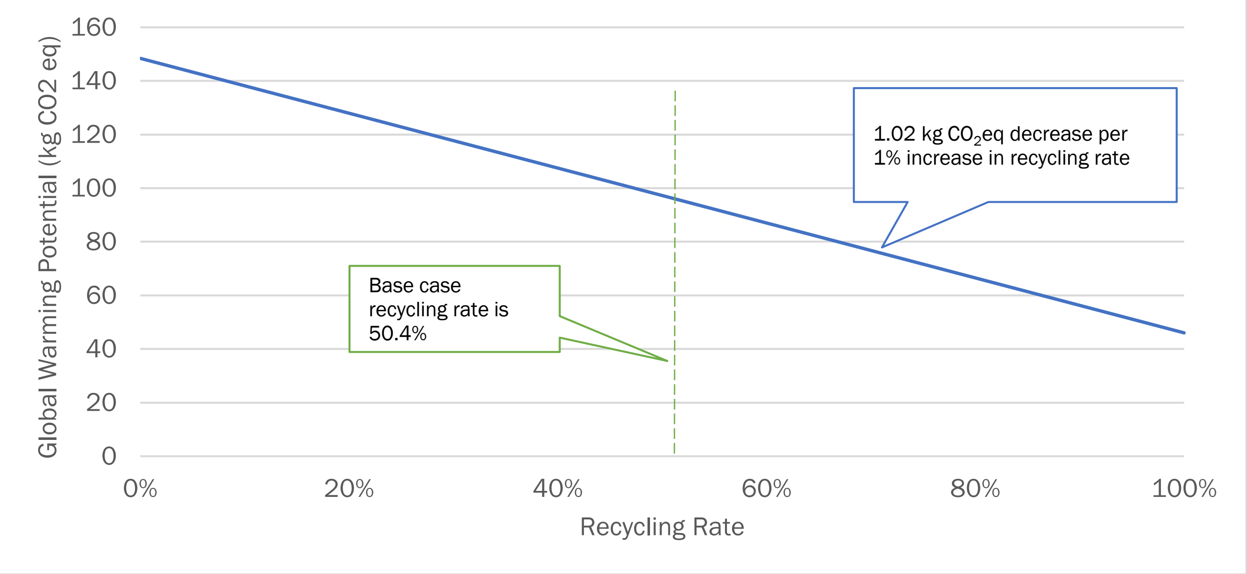


Figure ES-1: Effect of EoL recycling rate on cradle-to-grave GWP

The study also shows the impact of raw material usage on the environmental footprint of aluminum beverage cans. The contributions of individual life cycle stages to the total footprint (both cradle-to-gate and cradle-to-grave) are shown in Figure ES-2 and Figure ES-3. Although the average aluminum can contains only 27% primary aluminum, that input is responsible for the majority of the can's total life cycle environmental footprint. As such, reducing the use of primary aluminum while increasing the use of recycled aluminum can effectively reduce the cradle-to-gate footprint of the can.

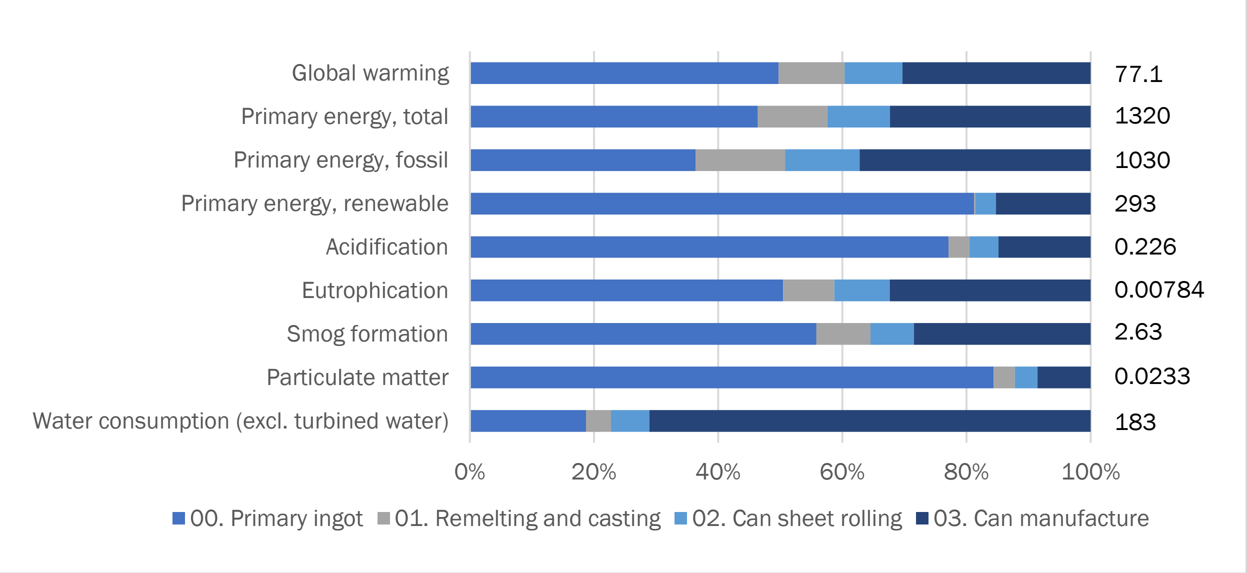


Figure ES-2: Selected LCI/LCIA results per 1,000 cans (cradle-to-gate)

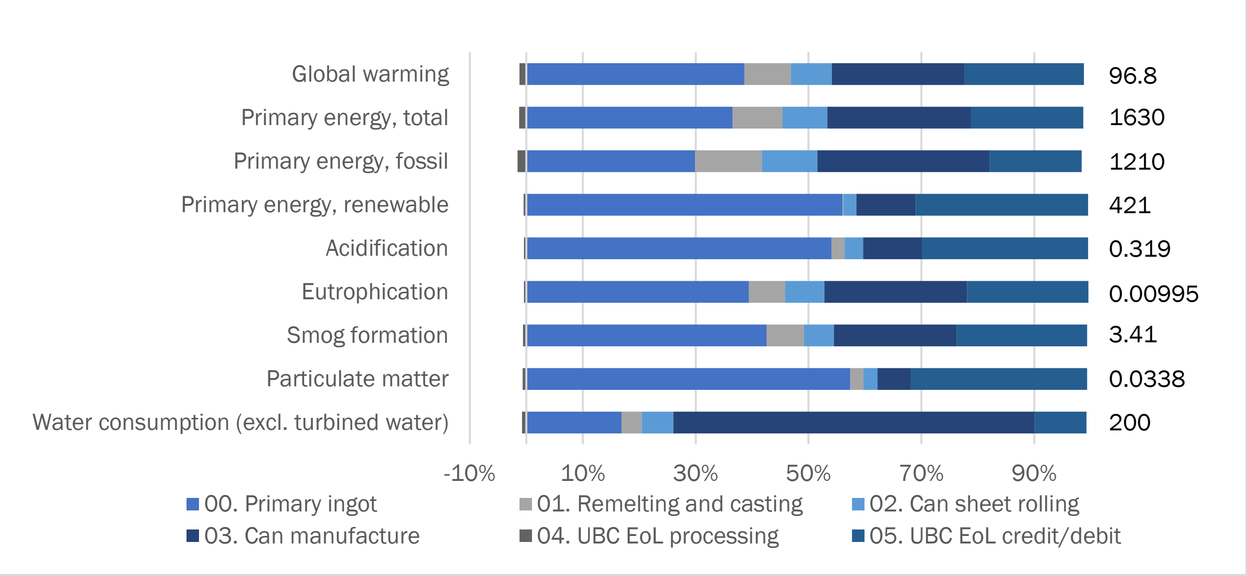


Figure ES-3: Selected LCI/LCIA results per 1,000 cans (cradle-to-grave)

Raw material sourcing is also critical, as not all primary aluminum is created equal. As seen in Figure ES-4, changing the source of primary aluminum can have a significant impact on the cradle-to-gate environmental footprint of the average aluminum can. For instance, primary aluminum sourced from Canada is made almost exclusively using renewable hydropower while primary aluminum made in China is made largely with coal-generated power. This difference can have a profound impact – an aluminum can made using the same content (in the current case 27%) of primary aluminum sourced in China would be almost twice as carbon intensive in production than the average North American can made today using a mixture of primary metal sourced from North America and several other countries. If aluminum can made in China used more primary aluminum and less recycled metal, the difference would be much wider.

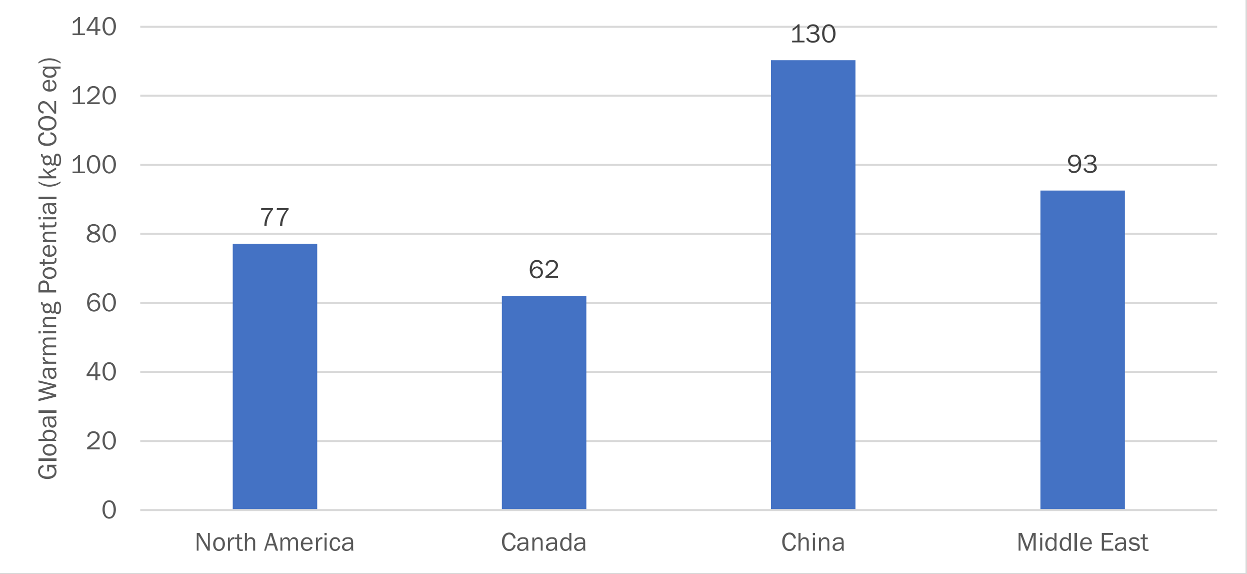


Figure ES-4: Effect of primary aluminum sourcing on cradle-to-gate GWP assuming the same primary aluminum content of 27 percent but changing its region of origin

Finally, it is important to place this study in a historical context to benchmark the progress made by the industry in reducing the environmental footprint of beverage cans over the years. As seen in Figure ES-5, the cradle-to-grave carbon footprint of aluminum cans has declined by 43% since 1991. The reduction between 2012 and 2016 is 7%. Reduction in primary energy demand is in a similar range (Figure ES-6). Much of the progress is attributable to the following:

- The metallic weight of an average can has declined by 18% from 15.83 grams to 12.99 grams per can, and per volume the decline is 27% from 1.32 grams per fluid ounce to 0.96 grams per fluid ounce;
- The environmental footprint of primary aluminum production in North America has been significantly reduced; and
- The manufacturing processes along the entire value chain have become far more efficient.

Unfortunately, one important parameter that could drive even more improvement in the aluminum can's environmental footprint is moving in the wrong direction. The end-of-life recycling rate for aluminum cans has dropped more than 10 percentage points – from more than 62% in 1991 to around 50% today. This deterioration offsets a significant amount of positive progress achieved in other areas over the years. The Aluminum Association advocates for many policies to increase the quality and quantity of used aluminum beverage cans coming back into the system. But increasing recycling in a meaningful way will require a wider effort involving hundreds of millions of individuals and stakeholders.

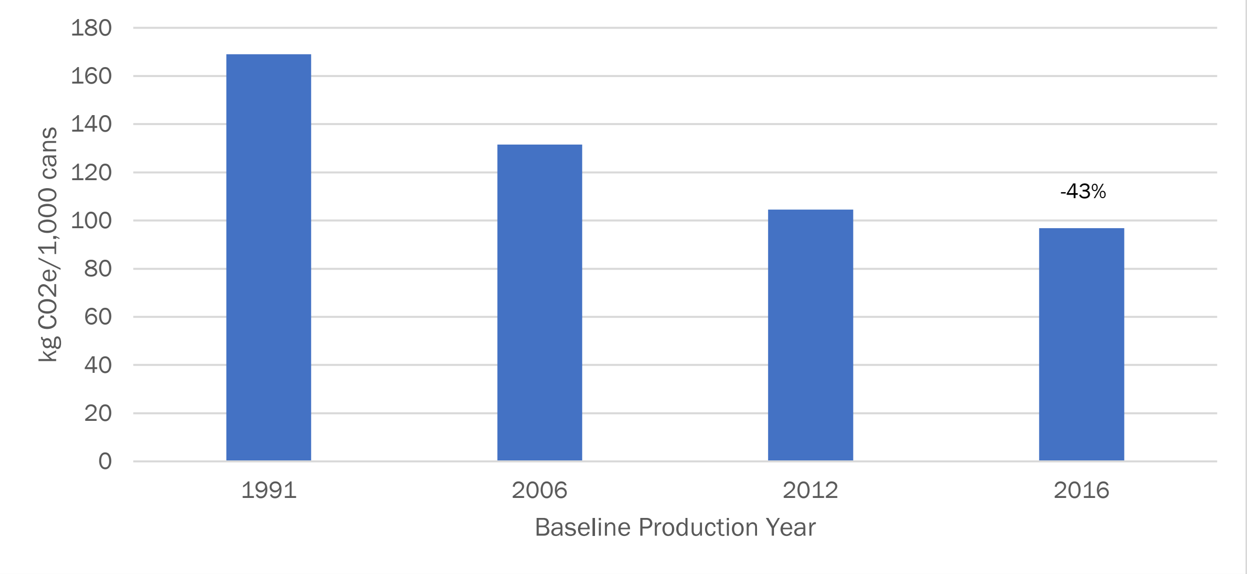


Figure ES-5: Cradle-to-grave reduction in carbon footprint of beverage cans in North America. Note: The sizes of cans are slightly different between studies.

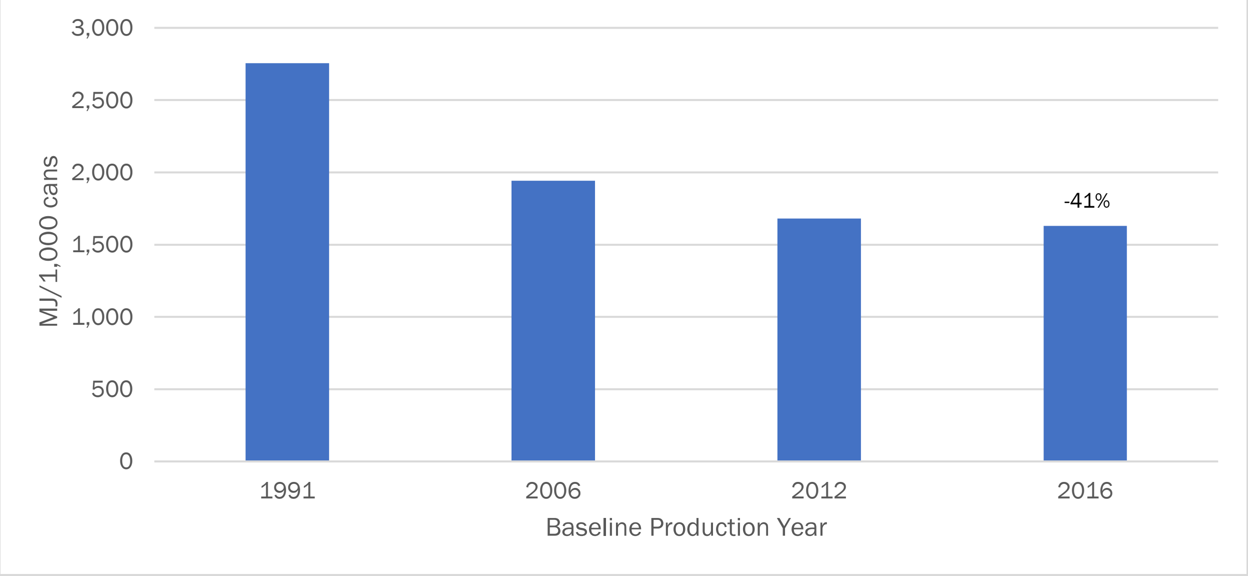


Figure ES-6: Cradle-to-grave reduction in primary energy demand of aluminum beverage cans in North America. Note: The sizes of cans are slightly different between studies.

Introduction

Life cycle assessment (LCA) is a quantitative and holistic methodology that assesses the potential environmental consequences of a product, process or service over its entire life cycle – from the extraction of raw materials (cradle) until the recycling or disposal of the product at the end-of-life (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 aluminum industry has been one of the pioneering material industries in adopting LCA to assess its products. Over the past three decades, a total of three LCAs have been done for aluminum beverage cans. Although these studies are slightly different in some aspects – including adopted standards, size of individual cans and, in some cases, scope of the study – they nevertheless enable the industry to track and benchmark its progress over time.

The 1993 Study

The first aluminum can study was completed in 1993. It was a life cycle inventory study of 1,000 cans with a single size of 12 oz beverage volume per can. It adopted guidelines titled A Technical Framework for Life Cycle Assessment (1991) developed by the Society of Environmental Toxicology And Chemistry (SETAC). Not only did the study include can production and recycling, but also beverage filling and distribution. The baseline year of production was 1991. The cradle-to-grave results of the study were based on a closed-loop substitution approach. Key parameters of beverage cans were:

- Metallic weight of an average can was 15.83 grams;
- Recycled content of average can was 80%. However, this was not a result of metal feedstock survey but a result of the LCA model which assumed closed-loop recycling – all can stamping scrap and recycled UBC scrap went back to can making. The true recycled content of cans was unknown. Finally;
- EoL recycling rate was 62.5%.

The 2010 Study

The second study was completed in 2010. It was a life cycle inventory and impact assessment of 1,000 cans with a variety of sizes representing shares of market shipment by each size in accordance with the International Standards ISO 14040 and 14044. The study did not include beverage filling, secondary packaging, and beverage distribution. The baseline production year was 2006. The study reported results for both cradle-to-gate and cradle-to-grave scopes. Cradle-to-gate results were calculated without assigning any upstream environmental burden to incoming scrap fractions, and cradle-to-grave results were based on a closed-loop substitution approach applied to the system's net scrap output. Key parameters of beverage cans were:

- Metallic weight of an average can was 13.34 grams and the beverage volume was estimated to be 12.4 oz;
- Recycled content was 67.8%, excluding internal rolling mill scrap; and
- EoL recycling rate was 51.6%.

The 2014 Study

The third study was completed in 2014. It was a life cycle inventory and impact assessment of 1,000 cans with a variety of sizes representing shares of market shipment by each size in accordance with the International Standards ISO 14040 and 14044. The study did not include beverage filling and distribution. The baseline production year was 2012. The study reported results for both cradle-to-gate and cradle-to-grave scopes. Cradle-to-gate results were calculated without assigning any upstream environmental burden to incoming scrap fractions, and cradle-to-grave results were based on a closed-loop substitution approach applied to the system's net scrap output. Key parameters of cans were:

- Metallic weight of an average can was 13.04 grams and no beverage volume information was reported;
- Recycled content was 70%, excluding internal rolling mill scrap; and
- EoL recycling rate was 54.6%.

These studies have helped the industry and its stakeholders understand the potential environmental impacts of beverage cans in great detail, enabling informed decision making and the identification of areas for improvements. In addition, the studies also helped the general public learn more about what they can do as individual consumers to contribute to the reduction of environmental impacts of beverage cans, particularly with regard to UBC recycling.

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

1. Goal of the Study

The aim of this study is to generate high-quality, up-to-date data on the environmental performance of aluminum beverage can production including the flow of secondary materials from EoL back into beverage cans. With such LCI data, the Aluminum Association and its member companies can assist other organizations to understand and communicate the environmental benefits of manufacturing with aluminum rather than other materials with similar physical properties. It provides useful insights for different stakeholder groups, such as primary or secondary aluminum producers, aluminum users, waste recyclers, government agencies, non-governmental organizations, LCA practitioners and media.

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

This LCA study has been carried out in accordance with the International Standard ISO 14044. It has been critically reviewed by an independent expert in accordance with ISO 14044, clause 6.1 to conform with all ISO requirements.

2. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.1. Product System(s)

The product system assessed in this study is aluminum beverage cans produced in North America and predominantly used for carbonated beverages (Figure 2-1). Based on the data collected for this study, the metallic weight of an average can is 12.99 grams, the recycled content is 73% (excluding internal rolling mill scrap), and the EoL recycling rate is 50.4%.

Figure 2-1: Aluminum beverage cans

2.2. Product Function(s), Functional Unit, and Reference Flow

The function of the beverage can is to serve as a container for mostly carbonated beverages such as beer or soft drinks. No other functions of the analyzed average beverage can are considered in this study.

Accordingly, the functional unit of the study is defined as the volume of beverage contained by 1,000 aluminum beverage cans with a weighted average can size of 13.6 fl oz per can, equaling 13,600 fl oz in total (106 gal or 402 L).

Based on this functional unit, the reference flow is calculated as 13.46 kg of finished aluminum cans.

2.3. System Boundaries

The product being examined is an average beverage can made of aluminum. It represents the current technological situation in the North American market.

The study is “cradle-to-grave” in scope, starting with the extraction of the bauxite ore at the mine, including the production/processing of aluminum ingot and the manufacturing of the aluminum beverage can, and ending after the recovery and recycling of the UBC. Table 2-1 summarizes the system boundaries with regard to the general processes/quantities that are considered in the study.

Table 2-1: System boundaries

Included	Excluded
✓ Raw materials extraction ✓ Energy and fuel inputs ✓ Further processing materials (e.g., chemicals, solvents, etc.) ✓ Processing of raw materials and semi-finished products ✓ Overhead (heating, lighting) of manufacturing facilities ✓ Transportation of raw and processed materials ✓ Product disposal and recycling	× Capital equipment and maintenance × Human labor and employee commute × Maintenance - of equipment × Manufacture of any beverage and its filling in cans × Internal transportation of materials × Packaging of cans for distribution to consumers × Distribution × Use of product

2.3.1. Time Coverage

The study aims to represent the calendar year 2016.

2.3.2. Technology Coverage

The study aims to represent the current manufacturing technologies employed by North American aluminum can sheet producers and can manufacturers.

2.3.3. Geographical Coverage

The study aims to represent the aluminum can industry in North America. Can sheet, can making and recycling/secondary metal production covers the United States and Canada. Primary aluminum production covers United States, Canada, and countries exporting primary ingot to North America. Alumina production and mining covers the global situation.

2.4. Allocation

2.4.1. Multi-output Allocation

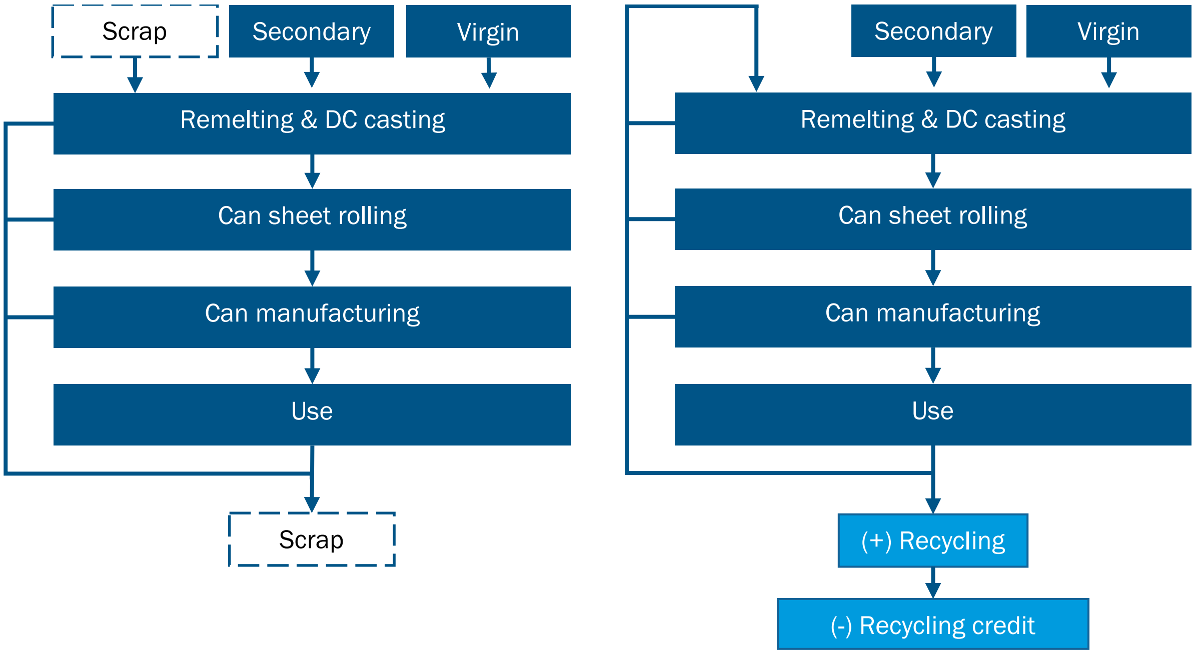
No co-product allocation was necessary in the foreground system of the study. Allocation of background data (energy and materials) taken from the GaBi 2020 databases is documented online at http://documentation.gabi-software.com/.

2.4.2. End-of-Life Allocation

End-of-Life allocation generally follows the requirements of ISO 14044, section 4.3.4.3. Such allocation approaches address the question of how to assign impacts from virgin production processes and the recycling activities to material that is recycled and used in future product systems. Common approaches to account for end-of-life recycling and recycled content in LCA are described below.

This study applies the embodied burden approach in its "**net scrap**" variant. It accounts for industry-average scrap inputs into can sheet production, the U.S. average end-of-life recycling rate and recycling yield of aluminum cans, and it uses the same consumption-based inventory of North American primary aluminum ingot that is also used in the manufacturing phase (i.e., the embodied burden) to assign a credit for recovered secondary aluminum. Sphera considers this approach to be the most sensible and internally consistent EoL allocation approach as it avoids both the uncertainties of estimating future substitution rates as well as the potential bias or net-negative results caused by crediting a different inventory than the one used in manufacturing. Other than the cut-off approach, it further ensures that any net scrap deficit of a product system is balanced by an additional burden of primary material by reversing the signs of the recycling and recycling credit in part (ii) of Figure 2-2. For a more detailed discussion, please refer to (Koffler & Finkbeiner, 2017).

- **Cut-off approach (also known as 100:0 or recycled content approach)** – The burdens of processing and recycling of any waste material sent to recycling is attributed to the subsequent, scrap-consuming product system and considered to be outside of the system boundary (i.e., they are "cut off"). The system boundary at end of life is drawn after scrap collection to account for the collection rate. Accordingly, any scrap inputs into the manufacturing stage are considered to be free of any upstream virgin material burdens (see part (i) of Figure 2-2). In cases where waste materials are sent to waste incineration, they are linked to an inventory that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. In cases where waste materials are sent to landfills, they are linked to an inventory that accounts for waste composition, landfill gas capture as well as utilization rates (flaring vs. power production). No credits for power or heat recovered from waste incineration or landfilling are assigned under the cut-off approach for consistency with the accounting approach for recycling.



(i) Cut-off approach

(ii) Substitution & embodied burden approach (net scrap)

Figure 2-2: Schematic representations of the end-of-life allocation approaches

- **Substitution approach (also known as 0:100 or end of life recycling approach)** – This allocation approach is based on the perspective that a material that is recycled into a secondary material at end of life will substitute another material based on technical substitutability. The substituted material can be the same material (closed loop recycling) or a different one (open loop recycling). If changes to the inherent material properties occur (i.e., changes in material quality), these need to be accounted for (downcycling/upcycling). Hence, a credit is given to account for the material substitution based on the mass and quality of the recovered secondary material.
  This also means that upstream burdens equivalent to the EoL net credit should be assigned to waste materials used as an input into the manufacturing stage to avoid double-counting the benefits of recycled contents (i.e., by receiving a credit at end-of-life for recycling a secondary material that entered the product system without any upstream burden of virgin material production).
  Mathematically, double-counting is avoided by first subtracting open scrap inputs into the manufacturing stage from scrap to be recycled at end of life to arrive at the overall “net scrap” output from the product life cycle. This remaining net scrap is then sent to material recycling and the recovered secondary material credited using a market-average inventory of the substituted material (see part (ii) of Figure 2-2). Note that the incoming scrap is not burdened with any upstream burden of virgin material production under the net scrap approach; instead, the EoL credit is reduced by reducing the amount of scrap that is sent to recycling. This leads to the exact same cradle-to-grave life cycle result without increasing the cradle-to-gate burden, and it incentivizes the use of recycled content without sacrificing EoL recycling credits like the cut-off approach does. Also note that the net scrap may become a negative amount in cases of high scrap demand in manufacturing and low collection rates in end-of-life. Such a *scrap deficit* in the product system would then be addressed the same way as the recycling and crediting of an excess of end-of-life scrap, but with a negative sign.
  Waste material sent to landfill or waste incineration is treated the same way as under the cut-off approach, but with the difference that recovered power and heat are addressed by crediting average grid electricity and thermal energy from natural gas, respectively.

- **Embodied burden approach** - This allocation approach is based on the perspective that a waste material that is recycled into a secondary material at end of life will take its embodied burdens of virgin material production with it into the next product system (think: relay race or environmental "backpack"). It therefore does not matter which material is substituted in the scrap-receiving product system; it only matters that the scrap-consuming product system accepts the net recycling credit allotted to the scrap-producing product system as the upstream burden of the received waste material. The embodied burden approach can be implemented with upstream virgin material burden added to the manufacturing phase or using the same net scrap approach described above. While it is hence very similar to the substitution approach described above in its mathematical structure (see also part (ii) of Figure 2-2), the main difference is that the recycling credit is always modeled using the same inventory data that was (or would have been) used to model virgin material production in the manufacturing stage.
  For example, while the above substitution approach may credit a global average inventory of virgin material because that waste material is a globally traded commodity (see for example (worldsteel, 2017)), the embodied burden approach would credit the same exact inventory that was used to model any virgin material contents in the manufacturing stage, which are usually specific to a country or region. Waste material sent to landfill or waste incineration is treated the same way as under the substitution approach.

2.5. Cut-off Criteria

No cut-off criteria are defined for this study. As summarized in section 2.3, the system boundary was defined based on relevance to the goal of the study. For the processes within the system boundary, all available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

The choice of proxy data is documented in Chapter 3. The influence of these proxy data on the results of the assessment has been carefully analyzed and is discussed in Chapter 5.

2.6. Selection of LCIA Methodology and Impact Categories

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-2 and Table 2-3. TRACI 2.1 has been selected as it is currently the only impact assessment methodology framework that incorporates US average conditions to establish characterization factors (Bare, 2012; EPA, 2012). For impact categories where TRACI characterization factors are not available (e.g., water footprinting) or where they are not considered to be the most current (e.g., global warming potential), alternative methods have been used and are described in more detail below.

Global Warming Potential, Non-Renewable Primary Energy Demand and total Primary Energy Demand were chosen because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be one of the most pressing environmental issues of our time. The global warming potential impact category is assessed based on the current IPCC characterization factors taken from the 5th Assessment Report (IPCC, 2013) for a 100-year timeframe (GWP) as this is currently the most commonly used metric. The global warming potential results exclude any photosynthetically bound carbon (also called *biogenic carbon)* as well as the release of that carbon as CO_2.

Eutrophication, Acidification, and Smog Formation Potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burden associated with commonly regulated emissions such as NO_x, SO_2, VOC, and others.

Particulate matter (PM2.5 equiv.) was included due to its relevance to air quality and human health. According to the World Health Organization (WHO), "air pollution-related deaths and illness are linked most closely to exposures to small particulate matter (PM) of less than 10 or 2.5 microns in diameter (PM10 and PM2.5). Small particulates bypass the body's defenses against dust, penetrating deep into the respiratory system. They also comprise a mixture of health-harming substances, such as heavy metals, sulphur compounds, carbon compounds, and carcinogens including benzene derivatives" (WHO, 2021).

The Montreal Protocol on Substances that Deplete the Ozone Layer was implemented in 1989 with the aim of phasing out emissions of ozone depleting gases. The protocol has been ratified by all members of the United Nations – an unprecedented level of international cooperation. With a few exceptions, use of chlorofluorocarbons, the most harmful chemicals, have been eliminated, while complete phase-out of less active hydrochlorofluorocarbons will be achieved by 2030. As a result, it is expected that the ozone layer will return to 1980 levels between 2050 and 2070. In addition, no ozone-depleting substances are emitted in the foreground system under study. For these reasons, ozone depletion potential is not considered in this study.

Blue water consumption, i.e., the anthropogenic removal of water from its watershed through shipment, evaporation, or evapotranspiration has also been selected due to its high political relevance. The UN estimates that roughly a billion people on the planet don't have access to improved drinking water, which entails a variety of problems around ecosystem quality, health, and nutrition. While a detailed water scarcity or water availability footprint was outside of the scope of this study, two water consumption metrics were considered: one with and one without inclusion of turbined water from hydropower generation. While the turbined water is technically "consumed" since hydropower dams may act as a man-made barrier between watersheds, it is not evaporated but remains in the surface water body. In addition, due to the high share of hydropower in the aluminum supply chain, the turbined water would dominate the water consumption results and divert attention from other sources of water consumption that are evaporative in nature and can therefore be argued to be of higher environmental concern. As such, the base results show water consumption values excluding turbined water, while water consumption results including turbined water are reported in Annex B.

The present study excludes the assessment of mineral resources, as despite 20 years of research, there remains no robust, globally agreed upon method - or even problem statement - for assessing mineral resource inputs in life cycle impact assessment (Drielsmaa, et al., 2016). One may further argue that the concern regarding the depletion of scarce resources is not as much an 'environmental' one, but rather about the vulnerability of markets to supply shortages. These shortages, in return, are driven by various factors that are not captured well by current metrics. Accordingly, resource criticality has emerged as a separate tool to assess resource consumption (Nassar, et al., 2012; Graedel & Reck, 2015). As a complete criticality assessment is out of scope for this work and the environmental interventions associated with the production and consumption of these resource are captured by the other impact categories the study at hand therefore excluded the assessment of abiotic resources.

Table 2-2: LCIA impact category descriptions

Impact Category	Description	Unit	Reference
Global Warming Potential (GWP), excluding biogenic CO_2	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	(IPCC, 2013)
Eutrophication Potential (EP)	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	kg N equivalent	(Bare, 2012) (EPA, 2012)
Acidification Potential (AP)	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	kg SO_2 equivalent	
Smog Formation Potential (SFP)	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg O_3 equivalent	
Particulate Matter (PM)	A measure of particulate matter emissions of various sizes. Small particulates bypass the body's defenses against dust, penetrating deep into the respiratory system. According to the WHO, most deaths and illnesses due to air pollution are most closely linked to exposures to small particulate matter (PM10 and smaller).	kg PM2.5 equivalent	

Table 2-3: Other environmental indicators

Indicator	Description	Unit	Reference
Primary Energy Demand (PED)	A measure of the total amount of primary energy extracted from the earth. PED can be distinguished into energy demand from non-renewable resources (e.g., petroleum, natural gas, etc.) and energy demand from renewable resources (e.g., hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g., power, heat, steam, etc.) are taken into account.	MJ NCV (net calorific value)	(Guinée, et al., 2002)
Water Consumption	A measure of the net intake and release of fresh water across the life of the product system. This is not an indicator of environmental impact without the addition of information about regional water availability.	Liters of water	(Sphera, 2020)

It shall be noted that the above impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

2.7. Interpretation to be Used

The results of the LCI and LCIA were interpreted according to the Goal and Scope. The interpretation addresses the following topics:

- Identification of significant findings, such as the main process step(s), material(s), and/or emission(s) contributing to the overall results
- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data.
- Conclusions, limitations and recommendations

2.8. Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- Measured primary data are considered to be of the highest precision, followed by calculated data, literature data, and estimated data. The goal is to model all relevant foreground processes using measured or calculated primary data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- Consistency refers to modeling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modeling choices, data sources, emission factors, or other artefacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to provide enough transparency with this report so that third parties are able to approximate the reported results. This ability may be limited by the exclusion of confidential primary data and access to the same background data sources.
- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope. The goal is to use the most representative primary data for all foreground processes and the most representative industry-average data for all background processes. Whenever such data were not available (e.g., no industry-average data available for a certain country), best-available proxy data were employed.

An evaluation of the data quality with regard to these requirements is provided in section 5 of this report.

2.9. Type and Format of the Report

In accordance with the ISO requirements (ISO, 2006), this document aims to report the cradle-to-gate and cradle-to-grave results and conclusions of the LCA completely, accurately and without bias to the intended audience. The results, data, methods, assumptions and limitations are presented in a transparent manner and in sufficient detail to convey the complexities, limitations, and trade-offs inherent in the LCA to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

2.10. Software and Database

The LCA model was created using the GaBi 10 software system for life cycle engineering, developed by Sphera Solutions, Inc. The GaBi 2020 LCI Databases provide the life cycle inventory data for several of the ancillary materials and processes obtained from the background system.

2.11. Critical Review

While the study is not intended to support any comparative assertions, a critical review was performed by a single independent expert in accordance with ISO 14044, clause 6.2. 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 data interpretations reflect the limitations identified and the goal of the study
- The study report is transparent and consistent

The review of this study was performed by Dr. Thomas Gloria, Ph.D., of Industrial Ecology Consultants LLC. The review comments and responses are available upon request from The Aluminum Association. A copy of the Critical Review Statement can be found in Annex A.

3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

All primary data were collected by The Aluminum Association using customized data collection templates. Primary data includes rolling ingot production, can sheet production, can manufacturing, primary aluminum, secondary aluminum and end-of-life recycling. Data collection started in 2017 and completed in 2019. Data collection covers all of North America and includes domestic primary aluminum producers, can sheet producers, and all major UBC and manufacturing scrap recyclers.

Different companies participated in the study to provide data for the various can sheet production stages and UBC/manufacturing scrap recycling, including Alcoa (the Alcoa can sheet business has since been acquired by Kaiser Aluminum), Constellium, Logan Aluminum, Novelis, and Tri-Arrows Aluminum. Data collected from can sheet production and UBC/manufacturing scrap recycling facilities covers more than 95% of total annual production.

Primary aluminum production data was directly collected from aluminum smelters by the International Aluminium Institute (IAI) and shared with the Aluminum Association. The shared data included aggregated data of North American domestic production as well as aggregated data of productions from relevant countries and regions where additional primary aluminum is imported by the North American aluminum semi-fabrication industry. The baseline production year is 2016 (with emissions data representing 2015 and energy data representing 2016).

Can manufacturing data was collected by the Can Manufacturers Institute for the production year of 2012 for the 2014 study. This study did not collect new can manufacturing data based on two considerations. One is that the data collection process is highly onerous for companies, given the amount of data points requested and the numerous operational records they must review. A second consideration is the assumption of little change to manufacturing technologies over the 4-year period. It is possible that operation efficiencies such as energy consumption and product yield have improved. However, given the onerous process of data collection and the impact to individual companies involved in the study, this part of the data update is left for the next study. The can manufacturing data covers 99% of total annual production.

3.2. Aluminum Can Production

3.2.1. Overview of Product System

This section describes the manufacturing of beverage cans as representative of North American market conditions, as depicted in Figure 3-1. The aluminum can life cycle begins with the casting of rolling ingot with a can-specific average recycled content of 73% (excluding internal rolling mill scrap). In total, 216 kg of primary aluminum ingot on average were purchased by the industry in 2016 to produce 1,000 kg of rolling ingot.

Next, the ingot is rolled into can sheet before being transported to the can manufacturer for can production.

Since the distribution, storage, and use stages are excluded from the system boundary, transportation to end-of-life waste management is the next life cycle stage considered. At end-of-life, UBC are split between landfilling

(49.6%) and recycling (50.4%) based on Aluminum Association data for the reference year 2016 (Aluminum Association, 2020).

Figure 3-1 further shows that the overall scrap balance of the product system, the so-called *net scrap*, is negative for North American aluminum cans since the scrap demand in manufacturing is higher than the scrap collected for recycling at end-of-life. For a positive net scrap balance, the model would subtract an equivalent amount of primary aluminum ingot based on the amount of secondary ingot recovered from the UBC scrap with a 94% recycling yield (according to survey data). For a negative scrap balance, however, the inventories used to model the recycling likewise change their sign, and what would be a net credit otherwise becomes a net burden.

The production of 1,000 cans at a can manufacturing plant requires 16 kg of aluminum sheet (inclusive to can body and lid). The can manufacturing process yields 3 kg of post-industrial aluminum scrap. To produce 16 kg of aluminum sheet, the total amount of aluminum ingot input required for the rolling process is 20.9 kg.

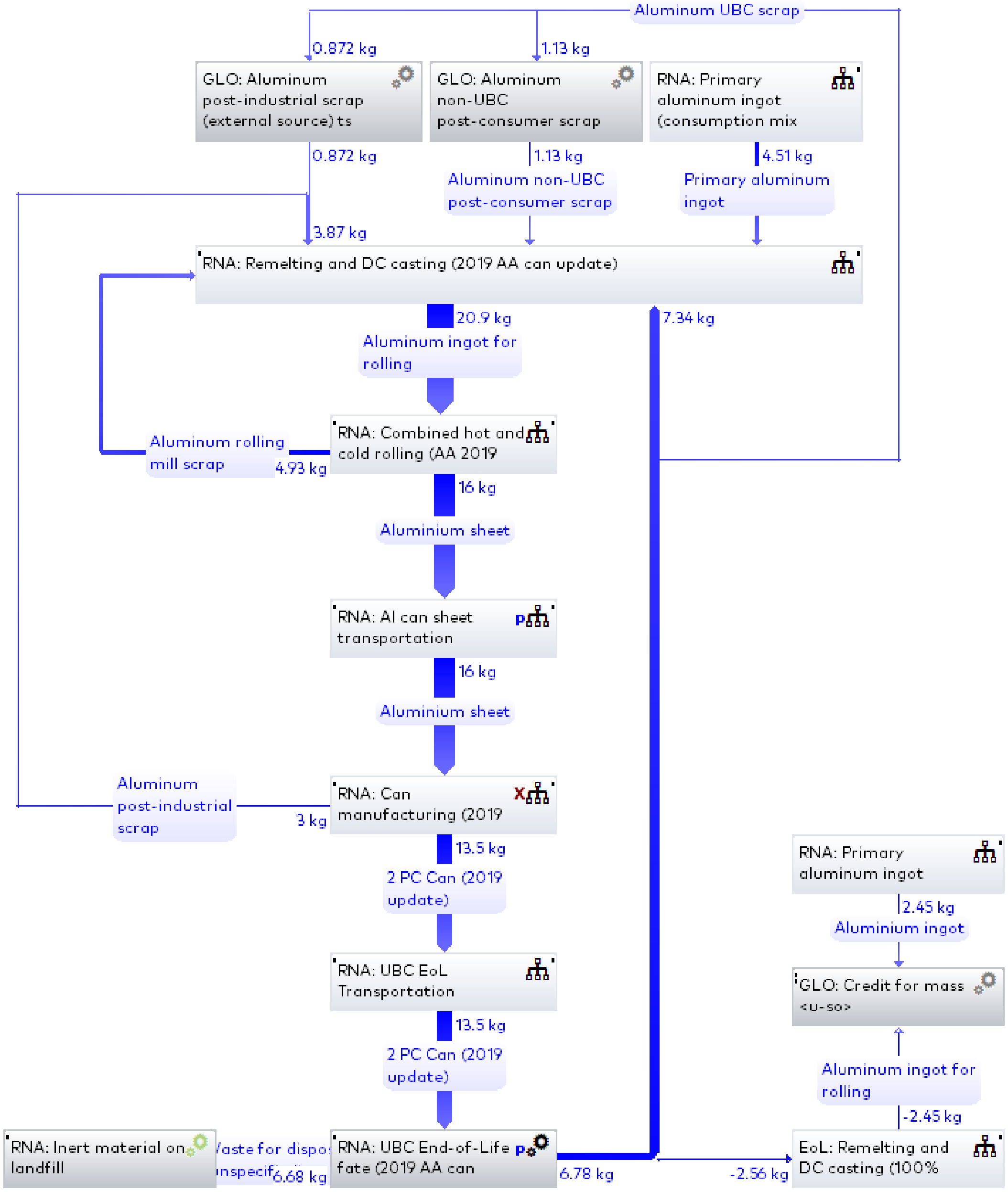


Figure 3-1: Cradle-to-grave life cycle inventory model of North American aluminum cans

3.2.2. Remelting, Casting and Sheet Rolling

The manufacturing of the aluminum beverage can begins with melting of aluminum scrap and aluminum ingots. The process is called a remelting & casting process. It is an integrated step of all can sheet makers. This remelting and casting step is also a recycling process; it starts with scrap treatment, then remelting, alloying and ingot casting. Treated aluminum post-consumer and pre-consumer scrap, together with primary and recycled aluminum ingots, are mixed and melted in the melting furnaces and then cast into ingots for rolling.

The rolling process converts aluminum ingots into can body stock and lid stock coil, which are subsequently converted into can bodies and lids at the can manufacturing plant. In hot mill rolling, aluminum ingots (approximately .457 to .660 meters thick and weighing approximately 15 to 30 metric tons) are preheated to about

1,000°F and fed through a hot reversing mill. In the reversing mill, the coil passes back and forth between rollers and the thickness is reduced from the initial thickness to between .0254 to .0508 meters with a corresponding increase in length. Following the reverse mills, the slabs are fed to a continuous hot mill where the thickness is further reduced to less than .00635 meters in thickness. The metal, called re-roll or hot coil, is rolled into coil and ready to be transferred to the cold mill.

Prior to the cold mill, the coils may be annealed to give the metal the workability for downstream processing. Some plants have moved towards self-annealing which requires no additional energy investment as the industry has improved their energy management. The coils are then passed through multiple sets of continuous rollers to reduce the gauge to approximately 0.000305 meters, as required by the can manufacturers. The coils are slit to the width and cut to the length required by can manufacturers and then packaged to prevent damage to the metal in shipping. Sheet rolling differs slightly based on the final use of the can sheet – for the body of the can or the lid. The main difference is that the can body sheet and lid sheet are not in the same alloy group.

Illustrations of the remelting and casting and sheet rolling processes are shown in Figure 3-2 and Figure 3-3 respectively. Table 3-1 lists the inputs and outputs of the remelting and casting process, and Table 3-2 lists the inputs and outputs of the sheet rolling process.

Figure 3-2: Gate-to-gate remelting and direct chill casting model

Table 3-1: Remelting and direct chill casting unit process

Type	Flow	Value	Unit
Inputs	Alloy components	9.71	kg
	Argon	247	kg
	Chlorine	0.000759	kg
	Electricity	337	MJ
	Filter media	0.182	kg
	Hydraulic oil	0.0114	kg
	Nitrogen gaseous	0.598	kg
	Potassium chloride	0.00488	kg
	Primary aluminum ingot	214	kg
	Quicklime	0.0737	kg
	Refractory	0.378	kg
	Secondary aluminum ingot	61.3	kg
	Sodium chloride (rock salt)	1.93	kg
	Sodium hydroxide (100%; caustic soda)	0.150	kg
	Sulphuric acid (100%)	0.0114	kg
	Thermal energy from diesel fuel	5.98	MJ
	Thermal energy from LPG	2.09	MJ
	Thermal energy from natural gas	3,780	MJ
	Aluminum non-UBC post-consumer scrap	41.6	kg
	Aluminum post-industrial scrap	167	kg
	Aluminum rolling mill scrap	235	kg
	Aluminum UBC scrap	321	kg
	Water	355	kg
Outputs	Aluminum ingot for rolling	1,000	kg
	Dross for recovery	41.2	kg
	Filter dust for recovery	2.70	kg
	Filter paper for disposal	0.207	kg
	Hazardous waste for disposal	0.0783	kg
	Refractory for disposal	0.792	kg
	Saltcake for recovery	1.06	kg
	Scrap metal for recovery, excluding aluminum	0.767	kg
	Unprocessed aluminum scrap	0.268	kg
	Waste for disposal (unspecified)	4.35	kg
Emissions to air	Dust (PM2.5)	0.0341	kg

Type	Flow	Value	Unit
	Dust (PM2.5 - PM10)	0.0540	kg
	Chlorine	0.00122	kg
	Hydrogen chloride	0.0322	kg
	Hydrogen fluoride	0.00646	kg
	Lead	4.64E-05	kg
	Nitrogen dioxide	0.0784	kg
	NMVOC	0.0362	kg
	Sulphur dioxide	0.000481	kg
	Water vapor	35.5	kg
Emissions to water	Aluminum	0.000203	kg
	Biological oxygen demand (BOD)	0.000298	kg
	Chromium	1.25E-07	kg
	Heavy metals	4.07E-05	kg
	Phosphorus	2.87E-05	kg

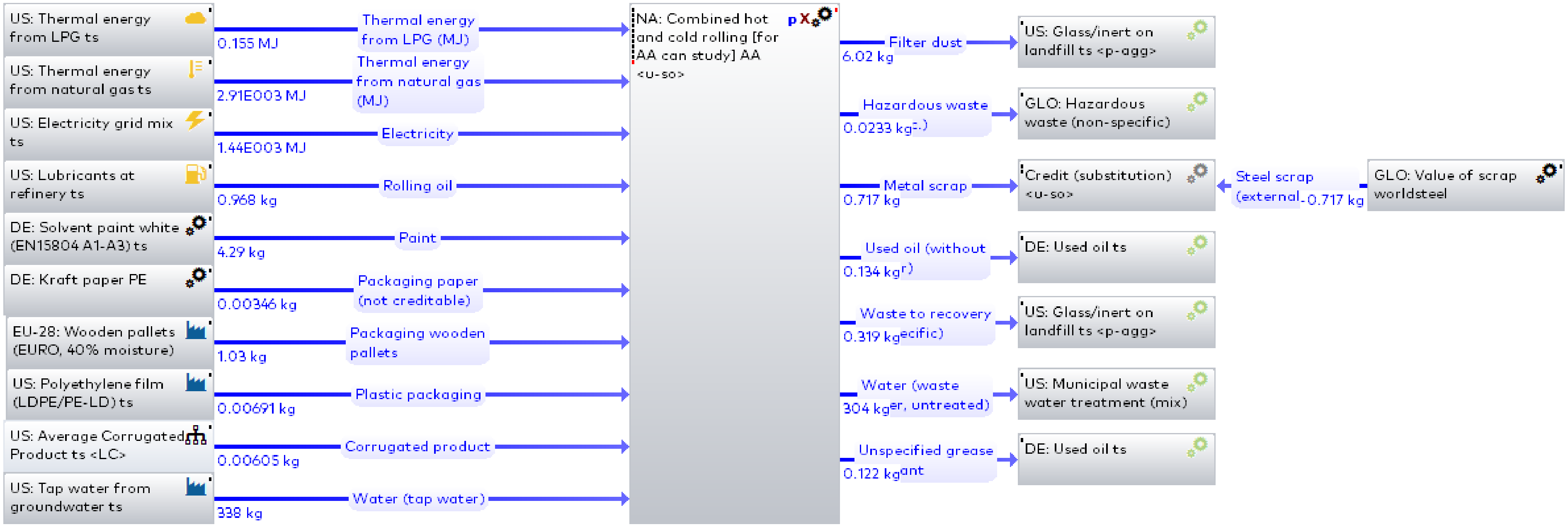


Figure 3-3: Gate-to-gate sheet rolling model

Table 3-2: Sheet rolling unit process

Type	Flow	Value	Unit
Inputs	Aluminum ingot for rolling	1,310	kg
	Cardboard packaging	0.00605	kg
	Electricity	1,440	MJ
	Packaging paper	0.00346	kg
	Packaging wooden pallets	1.03	kg
	Paint	4.29	kg
	Plastic packaging	0.00691	kg
	Rolling oil	0.968	kg
	Thermal energy from LPG	0.155	MJ
	Thermal energy from natural gas	2,910	MJ
	Water	338	kg
Outputs	Aluminum sheet	1,000	kg
	Aluminum scrap for recovery	308	kg
	Filter dust for recovery	6.02	kg
	Hazardous waste for disposal	0.0233	kg
	Metal scrap for recovery	0.717	kg
	Unspecified grease lubricant for disposal	0.122	kg
	Used oil (without water) for recovery	0.134	kg
	Waste to recovery (unspecific)	0.319	kg
	Wastewater	304	kg
Emissions to air	Dust (PM2.5 - PM10)	0.0181	kg
	Dust (PM2.5)	0.0215	kg
	Nitrogen dioxide	0.00906	kg
	NMVOC	0.203	kg
	Sulphur dioxide	0.0000415	kg
	Water vapor	33.8	kg
Emissions to water	Aluminum	0.000323	kg
	Chemical oxygen demand (COD)	0.0241	kg
	Chromium	0.000651	kg
	Organic compounds (unspecified)	0.0405	kg
	Phosphorus	0.00000864	kg

3.2.3. Can Manufacturing

After sheet rolling, aluminum coils are shipped from the rolling mills to can manufacturing plants. Within the can manufacturing plants, coils are set upright and moved into position to feed the cupping press. The coil is unwound and lubricated at a rate needed to feed the press. In the cupping press, blanks or discs are stamped and then pressed into cups. This process results in generation of manufacturing (skeleton) scrap which is then shipped back to recycling facilities. The cups then undergo a series of forming, ironing, and punching operations to form the final profile of the can as per the desired specifications. To ensure a flat top, the cans are trimmed at the top. The trim scrap is also shipped back to recycling facilities. After trimming, the cans undergo a series of washing steps before being dried in an oven. Paints are then applied externally to the cans, with the paint acting as a label for the can product. The cans are then internally coated to establish a barrier between the metal and beverage.

The next step, necking of the can, reduces the diameter of the open end of the can to match the diameter of the lid. The diameter of the lid is smaller than the can diameter, allowing for an overall reduction in the amount of aluminum used in a finished aluminum can. After the diameter has been reduced, the flange that forms part of the seal to the lid is formed. The cans then undergo a quality control process to check the integrity of the final product before they are shipped to fillers.

The cans are stacked onto plastic pallets for shipping. Layers of cans are separated using corrugated paper or plastic sheets. The entire pallet is then banded together with plastic bands and, in rare cases, is covered with shrink wrap to protect the cans from damage and dirt during both shipping and storage.

Can lids are manufactured from a different alloy than can body. Alloys for can lids have higher magnesium content in place of the manganese used in the bodies as lids are designed to be stiffer than the can body. Following the cold rolling, the can stock for lids is cleaned and coated and shipped to the manufacturer. Lids can be manufactured from either coils or from scrolled sheets. The manufacturing steps are very similar, independent of the type of feed, so only the coil-fed process is described here. The major steps in the process are stamping out ends, curling the edges of the shells, applying the sealing compound, stamping tabs, stamping the end features onto the ends, and finally attaching the tabs to the ends to make a completed lid. An illustration of the can making process is shown in Figure 3-4. Table 3-3 lists the inputs and outputs of the can-making process.

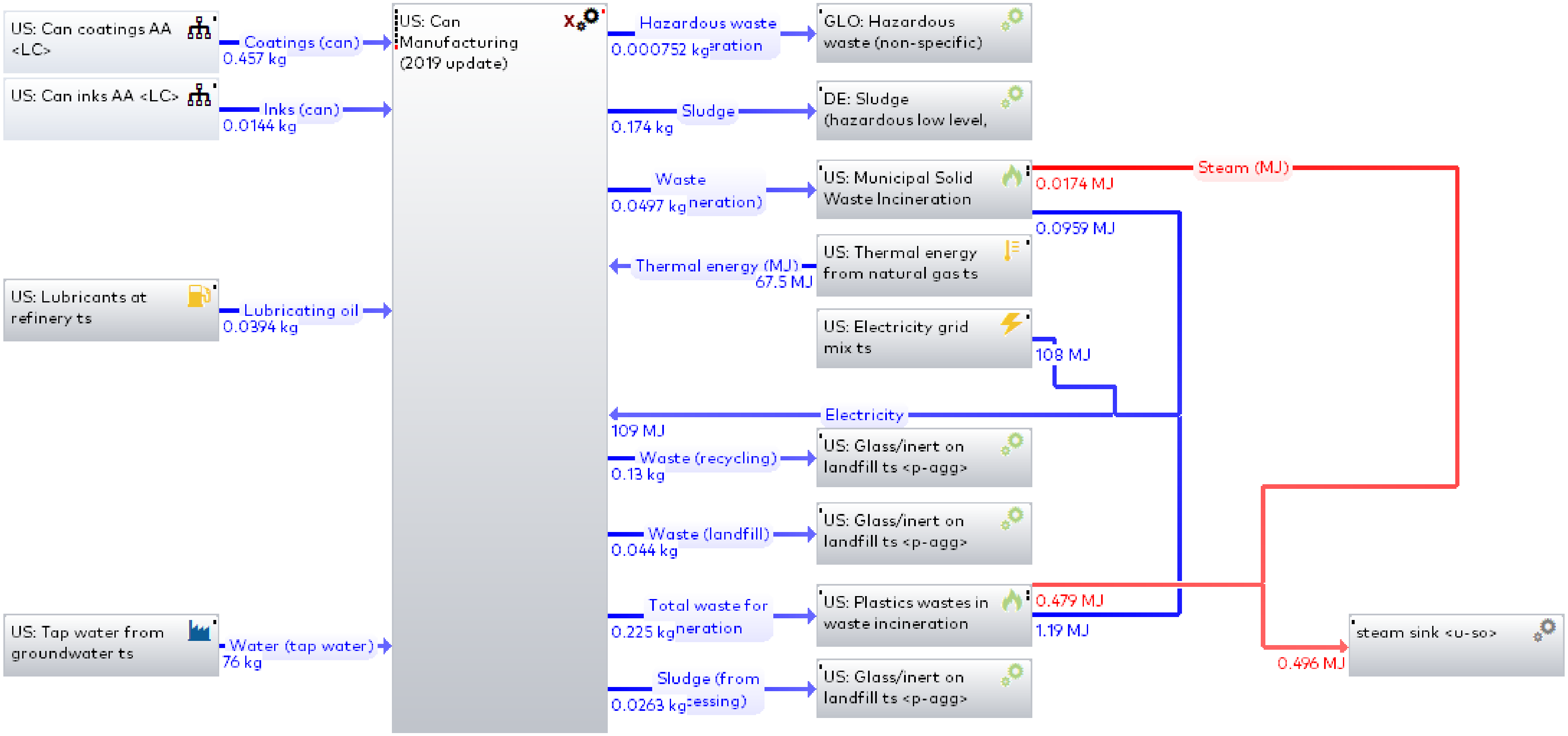


Figure 3-4: Gate-to-gate can manufacturing model

Table 3-3: Can manufacturing unit process

Type	Flow	Value	Unit
Inputs	Aluminum sheet	16.0	kg
	Coatings	0.457	kg
	Electricity	109	MJ
	Inks	0.0144	kg
	Lubricating oil	0.0394	kg
	Thermal energy from natural gas	67.5	kg
	Water	76.0	kg
Outputs	2-piece aluminum can	13.5	kg
	Aluminum post-industrial scrap for recovery	2.50	kg
	Hazardous waste for incineration	0.000752	kg
	Sludge for disposal	0.174	kg
	Sludge for recovery	0.0263	kg
	Waste for incineration	0.0275	kg
	Waste for landfilling	0.0440	kg
	Waste for recovery	0.130	kg
	Wastewater	53.4	kg
Emissions to air	Dust (PM10)	0.0000169	kg
	Nitrogen dioxide	0.00274	kg
	Nitrous oxide	0.000137	kg
	NMVOC	0.0648	kg
	Sulphur dioxide	0.0000163	kg
	Water vapor	22.6	kg

3.2.4. End-of-life

The used beverage container recycling process includes the unit process for remelting and secondary ingot casting which follows the process outlined in section 3.2.2. The secondary aluminum ingot is produced from pre-consumer and post-consumer scrap recovered from both the industrial and consumer waste stream. The UBCs may be collected in municipal curbside programs, dropped off programs, or deposit programs. UBCs collected by drop-off and deposit programs are much cleaner than those recovered from single-stream curbside recycling programs. UBCs must be treated prior to their melting in a furnace. First, the UBCs are shredded to remove trapped water and other contaminants. The uniform size of the shreds helps material flow in downstream processing. The shreds are passed under magnetic separators to remove ferrous contamination. In some facilities, air knives are also used to prevent the inclusion of heavy contamination such as lead, stainless steel, or zinc.

The metal leaves the shredders and passes into a decoating unit. This unit heats the metal and coatings, resulting in the vaporization and oxidation of the coatings. The decoating process results in the transfer of the hot metal to the melting furnace. Primary aluminum metal is consumed to make up for system melt loss and sweeten the composition if necessary. In addition, alloying additives are also added to meet the final specifications of the ingot to be produced.

It is important to note that the inventory data are specific for aluminum ingots used in can making and are not representative of secondary aluminum ingot production in general.

3.3. Background Data

3.3.1. Fuels and Energy

National averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2020 Databases. Table 3-4 shows the most relevant LCI datasets used in modeling the product systems. Electricity consumption was modeled using regional grid mixes.

Documentation for all GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-database-2020-lci-documentation/.

Table 3-4: Key fuel and energy datasets used in inventory analysis

Location	Dataset	Data Provider	Reference Year
US	Diesel mix at refinery	Sphera	2016
US	Electricity from biomass (solid)	Sphera	2016
US	Electricity from heavy fuel oil (HFO)	Sphera	2016
US	Electricity from hydro power	Sphera	2016
CA	Electricity from hydro power	Sphera	2016
US	Electricity from lignite	Sphera	2016
US	Electricity from natural gas	Sphera	2016
US	Electricity from nuclear	Sphera	2016
US	Electricity from wind power	Sphera	2016
US	Electricity grid mix	Sphera	2016
AU	Electricity grid mix	Sphera	2016
BR	Electricity grid mix	Sphera	2016
ZA	Electricity grid mix	Sphera	2016
US	Heavy fuel oil at refinery (0.3wt.% S)	Sphera	2016
US	Thermal energy from diesel	Sphera	2016
US	Thermal energy from hard coal	Sphera	2016
US	Thermal energy from heavy fuel oil (HFO)	Sphera	2016
ZA	Thermal energy from heavy fuel oil (HFO)	Sphera	2016
BR	Thermal energy from heavy fuel oil (HFO)	Sphera	2016
ZA	Thermal energy from light fuel oil (LFO)	Sphera	2016
BR	Thermal energy from light fuel oil (LFO)	Sphera	2016
US	Thermal energy from light fuel oil (LFO)	Sphera	2016
US	Thermal energy from LPG	Sphera	2016
EU-28	Thermal energy from LPG	Sphera	2016

Location	Dataset	Data Provider	Reference Year
US	Thermal energy from natural gas	Sphera	2016
US	Thermal energy from LPG	Sphera	2016

3.3.2. Transportation

The GaBi 2020 database was used to model transportation. Truck transportation within the United States was modeled using the GaBi US truck transportation datasets. Fuels were modeled using the geographically appropriate datasets. Table 3-5 shows the most relevant LCI datasets used in modeling the product systems.

Documentation for all GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-database-2020-lci-documentation/.

Table 3-5: Key transportation datasets used in inventory analysis

Location	Dataset	Data Provider	Reference Year
GLO	Bulk commodity carrier, average, ocean going	Sphera	2019
GLO	Container ship, 5,000 to 200,000 dwt payload capacity, ocean going	Sphera	2019
GLO	Large Engine ship, 3'000t payload capacity / canal	Sphera	2019
GLO	Rail transport cargo - average, average train, gross tonne weight 1,000t / 726t payload capacity	Sphera	2019
US	Truck - Dump Truck / 52,000 lb payload - 8b	Sphera	2019
GLO	Truck-trailer, Euro 4, 34 - 40t gross weight / 27t payload capacity	Sphera	2019

3.3.3. Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2020 database. Table 3-6 shows the most relevant LCI datasets used in modeling the product systems.

Documentation for all GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-database-2020-lci-documentation/.

Table 3-6: Key material and process datasets used in inventory analysis

Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
EU-28	Aluminium fluoride	Sphera	2018	Geo.
DE	Aluminium fluoride	Sphera	2019	Geo.
RNA	Aluminum ingot mix	AA/Sphera	2016	No
CA	Aluminium ingot mix	IAI	2015	No
CN	Aluminium ingot mix	IAI	2015	No
GLO	Aluminium ingot mix	IAI	2015	No

Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
RLA	Aluminium ingot mix	IAI	2015	No
RME	Aluminium ingot mix	IAI	2015	No
RU	Aluminium ingot mix	IAI	2015	No
US	Ammonium sulphate, by product acrylonitrile, hydrocyanic acid	Sphera	2019	No
US	Argon (gaseous)	Sphera	2019	No
US	Average Corrugated Product (Cradle-to-Gate, 2014)	CPA	2017	No
US	Benzene (from pyrolysis fuel)	Sphera	2019	No
DE	Carbon black (furnace black; deep black pigment)	Sphera	2019	Geo.
US	Chlorine mix	Sphera	2019	No
DE	Coal tar pitch (CTP) via distillation of coke-oven coal tar	Sphera	2019	Geo.
DE	Copper sulphate as by-product from copper route (import from CA)	Sphera	2018	Geo.
US	Dipropylene glycol by product propylene glycol via PO hydrogenation	Sphera	2019	No
DE	Epoxy Resin (EP)	Sphera	2019	Geo.
DE	Ethylene glycol	Sphera	2019	Geo.
US	Ethylene glycol (from ethene and oxygen via EO)	Sphera	2019	No
US	Ferro metals on landfill, post-consumer	Sphera	2019	No
EU-28	Fire proof stones (alumina-rich)	Sphera	2019	Geo.
DE	Formaldehyde (HCHO; 37%)	Sphera	2019	Geo.
US	Glass/inert on landfill	Sphera	2019	No
US	Hazardous waste in waste incineration plant	Sphera	2019	No
US	Isopropanol (highly pure)	Sphera	2018	No
DE	Kraft paper	Sphera	2010	Geo.
US	Lime (CaO; quicklime lumpy)	Sphera	2019	No
DE	Lime (CaO; quicklime lumpy)	Sphera	2019	Geo.
US	Lubricants at refinery	Sphera	2016	No
DE	Melamine Resin (MF)	Sphera	2019	Geo.
DE	Methanol from natural gas (integrated technologies)	Sphera	2019	Geo.
US	Municipal Solid Waste Incineration Plant	Sphera	2019	No
US	Municipal waste water treatment (mix)	Sphera	2019	No
US	Naphtha at refinery	Sphera	2016	No
US	Nitrogen (gaseous)	Sphera	2019	No
US	Petroleum coke at refinery	Sphera	2016	No

Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
DE	Phthalic anhydride	Sphera	2019	Geo.
US	Plastics wastes in waste incineration plant	Sphera	2019	No
EU-28	Polyester (PET) fabric	Sphera	2019	Geo.
US	Polyethylene film (LDPE/PE-LD)	Sphera	2019	No
EU-28	Polypropylene (PP) - fabric	Sphera	2019	Geo.
US	Potassium chloride (agrarian)	Sphera	2019	No
DE	Recycling potential steel sheet	Sphera	2018	Geo.
DE	Sludge (hazardous low level, encapsulation and landfill)	Sphera	2019	Geo.
US	Sodium chloride (rock salt)	Sphera	2019	No
US	Sodium hydroxide (caustic soda) mix (100%)	Sphera	2019	No
DE	Solvent paint white (EN15804 A1-A3)	Sphera	2019	Geo.
DE	Steel cold rolled coil	Sphera	2019	Geo.
DE	Steel sheet 0.75mm HDG (0.01mm Zn; 1side)	Sphera	2019	Geo.
US	Sulphuric acid aq. (96%)	Sphera	2019	No
EU-28	Talcum powder (filler)	Sphera	2019	Geo.
US	Tap water from groundwater	Sphera	2018	No
US	Tap water from surface water	Sphera	2019	No
US	Titanium dioxide pigment (sulphate process)	Sphera	2019	No
US	Urea (stamicarbon process)	Sphera	2019	No
DE	Used oil	Sphera	2019	Geo.
GLO	Value of scrap	worldsteel	2017	No
US	Water deionized	Sphera	2019	No
EU-28	Wooden pallets (EURO, 40% moisture)	Sphera	2018	Geo.

* Geo. = Geographical proxy; Tech. = Technological proxy

3.4. Life Cycle Inventory

ISO 14044 defines the LCI result as the “outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment”. As the complete inventory comprises hundreds of flows, Table 3-7 only displays a selection of flows based on their relevance to the subsequent impact assessment in order to provide a transparent link between the inventory and impact assessment results.

Table 3-7: Selected life cycle inventory results per 1,000 cans

Flow	Primary Ingot	Remelting & DC Casting	Sheet Rolling	Can Manufacturing	UBC EoL Processing	UBC EoL Credit
Energy (MJ)						
Non-renewable energy	3.73E+02	1.47E+02	1.23E+02	3.81E+02	-1.96E+01	2.03E+02
Hydroelectric energy	2.33E+02	-4.67E+00	2.27E+00	1.06E+01	-1.66E+00	1.27E+02
Other renewable energy (except hydro)	4.85E+00	5.27E+00	7.49E+00	3.42E+01	-3.80E-01	2.64E+00
Resources (kg)						
Bauxite	2.45E+01	-6.49E-01	3.23E-04	2.26E-03	-1.54E-01	1.33E+01
Net fresh water (excluding hydro power energy)	3.42E+01	7.33E+00	1.14E+01	1.30E+02	-1.53E+00	1.87E+01
Emissions to air (kg)						
Carbon dioxide	3.53E+01	7.42E+00	6.59E+00	2.17E+01	-1.10E+00	1.92E+01
Carbon monoxide	1.13E-02	2.31E-03	4.05E-03	1.00E-02	3.29E-04	6.15E-03
Chlorine	9.92E-07	2.55E-05	3.78E-07	6.24E-07	-3.00E-06	5.40E-07
Fluorine/Fluorides	1.63E-03	-4.38E-05	9.10E-07	4.28E-06	-1.04E-05	8.89E-04
Hydrogen chloride	5.41E-04	8.42E-04	1.45E-04	6.55E-04	-1.26E-04	2.95E-04
Hydrogen fluoride	1.65E-03	1.21E-04	4.54E-06	1.97E-05	-3.65E-05	9.01E-04
Nitrogen oxides	5.82E-02	7.84E-03	6.87E-03	2.08E-02	-9.98E-04	3.17E-02
Nitrous oxide	4.08E-04	6.36E-05	7.80E-05	4.48E-04	-8.97E-06	2.22E-04
Sulphur oxides	5.91E-18	4.20E-18	5.50E-18	2.54E-17	-2.04E-19	3.22E-18
Non-methane VOCs	4.44E-03	2.22E-03	4.56E-03	6.79E-02	-2.21E-04	2.42E-03
Methane	4.66E-02	2.58E-02	1.93E-02	5.35E-02	-3.58E-03	2.54E-02
Dust (PM10)	3.01E-03	1.45E-04	1.03E-06	5.66E-05	-8.51E-05	1.64E-03
Dust (PM2.5)	9.01E-03	7.13E-04	5.32E-04	6.45E-04	-1.44E-04	4.91E-03
Emissions to water (kg)						
Biological oxygen demand (BOD)	6.44E-05	3.53E-05	6.33E-05	7.61E-05	-5.87E-06	3.51E-05
Chemical oxygen demand (COD)	1.43E-02	2.33E-03	4.02E-03	1.61E-02	-3.96E-04	7.80E-03
Heavy metals	1.89E-01	-2.99E-03	2.91E-03	1.36E-02	-1.66E-03	1.03E-01
Ammonia	4.48E-06	6.01E-06	8.26E-06	3.86E-05	-7.76E-07	2.44E-06
Fluorine/Fluorides	7.44E-03	-9.25E-05	1.57E-04	7.85E-04	-4.29E-05	4.05E-03
Phosphate	1.91E-05	5.49E-06	6.36E-06	3.03E-05	2.55E-06	1.04E-05
Emissions to soil (kg)						
Total waste (excluding mining overburden)	1.78E+01	7.15E-01	4.39E-01	1.79E+00	6.58E+00	9.70E+00

4. LCIA Results

This chapter contains the results for the impact categories and additional metrics defined in section 2.6. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

4.1. Overall Results

4.1.1. Cradle-to-Gate

Table 4-1 presents cradle-to-gate life cycle impact assessment results, while Figure 4-1 depicts these results. As seen in Figure 4-1, primary ingot and can manufacturing have the greatest contributions across all indicators. The average contribution of primary ingot across all indicators is 58%, with an 84% contribution to particulate matter. It is important to note that primary aluminum is only 26.6% of raw metal input and the rest is recycled aluminum. The significant impact from primary aluminum is apparent. The average contribution of can manufacturing is 29%, with the highest contribution being 71% for water consumption (excl. turbined water).

Table 4-1: LCI and LCIA indicator results per 1,000 cans (cradle-to-gate)

Indicator	Unit	Primary Ingot	Re-melting and casting	Can sheet rolling	Can manufacturing	Total
Global warming	kg CO2 eq.	38.4	8.17	7.19	23.4	**77.1**
Primary energy, total	MJ	611	148	133	426	**1320**
Primary energy, fossil	MJ NCV	373	147	123	381	**1,030**
Primary energy, renewable	MJ	238	0.592	9.76	44.7	**293**
Acidification	kg SO2 eq.	0.174	0.0754	0.0106	0.335	**0.226**
Eutrophication	kg N eq.	0.00396	0.000644	0.000700	0.00254	**0.00784**
Smog formation	kg O3 eq.	1.47	0.229	0.185	0.750	**2.63**
Particulate matter	kg PM2.5 eq.	0.0197	0.000793	0.000849	0.00200	**0.0233**
Water consumption (excl. turbined water)	kg	34.2	7.33	11.4	130	**183**

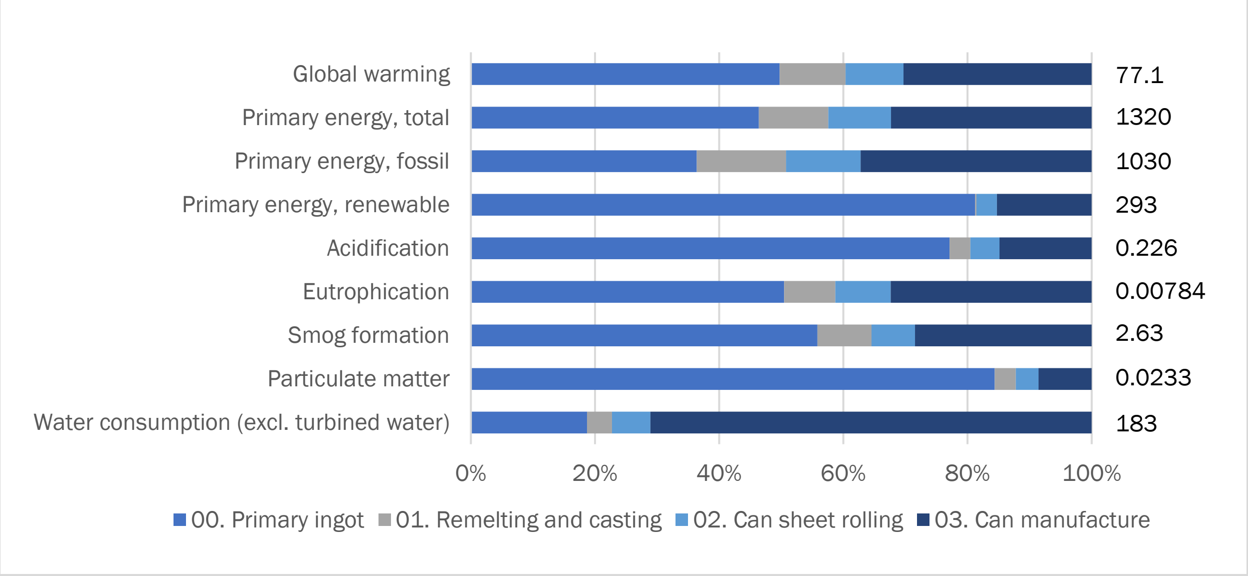


Figure 4-1: Relative contributions for LCI and LCIA indicator results per 1,000 cans (cradle-to-gate)

4.1.2. Cradle-to-Grave

Results are presented in this section over the full life cycle, i.e., from cradle to grave. Table 4-2 presents life cycle impact assessment results, while Figure 4-2 depicts these results. As seen in Figure 4-2, primary ingot, can manufacturing and credit/debit for primary ingot at EoL show the greatest contributions across all indicators.

Primary ingot has an average overall contribution of 43%, with its highest contribution being 58% to particulate matter. Can manufacturing has an average overall contribution of 23%, with its highest contribution being 65% to water consumption (excl. turbined water). The credit/debit for primary ingot at EoL has an average overall contribution of 24%, with its highest contribution being at 32% to particulate matter.

The contribution of EoL processing is negative and the EoL credit/debit is positive due to the fact that more scrap is required for can production than is collected for recycling at end-of-life (as seen in Figure 3-1). All cans that are recovered at end-of-life are used in the can manufacturing process. However, since the amount of cans recovered cannot meet can production demand, additional primary ingot is required to provide for the scrap deficit of the product system. Compared not a net scrap surplus, EoL processing and credit therefore change their signs such that the now positive “debit” becomes a further burden on the product system.

Table 4-2: LCI and LCIA indicator results per 1,000 cans (cradle-to-grave)

Indicator	Unit	Primary Ingot	Re-melting and casting	Can sheet rolling	Can manufacturing	UBC EoL Processing	UBC EoL Credit/ Debit	Total
Global warming	kg CO2 eq.	38.4	8.17	7.19	23.4	-1.22	20.9	**96.8**
Primary energy, total	MJ	611	148	133	426	-22	333	**1630**
Primary energy, fossil	MJ NCV	373	147	123	381	-19.6	203	**1,210**
Primary energy, renewable	MJ	238	0.592	9.76	44.7	-2.04	130	**421**
Acidification	kg S02 eq.	0.174	0.0754	0.0106	0.335	-0.00141	0.0948	**0.319**

Indicator	Unit	Primary Ingot	Re-melting and casting	Can sheet rolling	Can manufacturing	UBC EoL Processing	UBC EoL Credit/ Debit	Total
Eutrophication	kg N eq.	0.00396	6.44E-04	0.000700	0.00254	-4.23E-05	0.00216	**0.00995**
Smog formation	kg O3 eq.	1.47	0.229	0.185	0.750	-0.0210	0.801	**3.41**
Particulate matter	kg PM2.5 eq.	0.0197	7.93E-04	0.000849	0.00200	-2.21E-04	0.0107	**0.0338**
Water consumption (excl. turbined water)	kg	34.2	7.33	11.4	130	-1.53	18.7	**200**

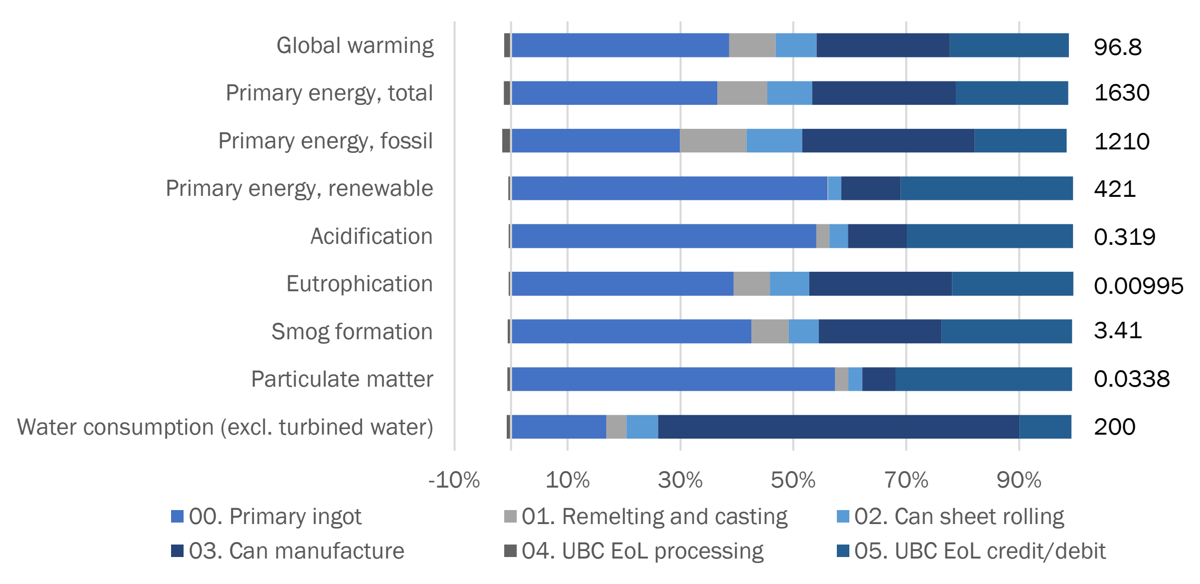


Figure 4-2: Relative contributions for LCI and LCIA indicator results per 1,000 cans (cradle-to-grave)

Below, Figure 4-3 depicts the cradle-to-grave GWP of each life cycle stage. In line with the results from previous tables, primary ingot has the greatest contribution to climate change with a 40% contribution. Again, it is important to remind readers that primary metal is only approximately 27% of the raw material input and the rest of the can is from recycled metal. Can manufacturing has the second highest contribution to climate change with a relative contribution of 24%. Finally, the positive EoL debit (i.e., the burden of primary ingot used to address the scrap deficit in production) has a contribution to climate change of 22%.

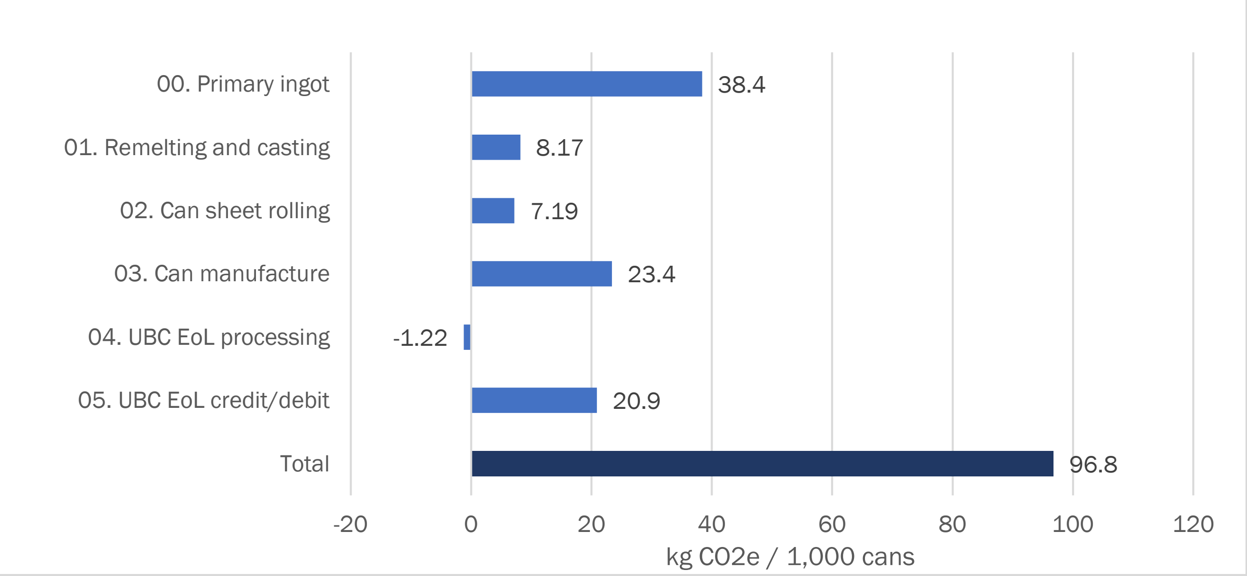


Figure 4-3: Global Warming Potential contributions per 1,000 Al cans (13.46 kg, net scrap w/ embodied burden debit)

4.1.3. Results for Various Conversions

Table 4-3 and Table 4-4 list the cradle-to-gate and cradle-to-grave results for a variety of units to assist readers for their specific needs. Results are presented for the -units of one can, one ounce of beverage, one liter of beverage, and one gallon of beverage. They represent simple conversions of the results for the functional unit of 1,000 cans with an average beverage volume of 13.6 fluid ounces.

Table 4-3. Cradle-to-gate results for various conversions

Indicator	Unit	One thousand (1,000) cans	One (1) can	One (1) ounce of beverage	One (1) liter of beverage	One (1) gallon of beverage
Global warming	kg CO2 eq.	77.1	0.0771	0.00567	0.192	0.726
Primary energy, total	MJ	1320	1.32	0.0971	3.28	12.4
Primary energy, fossil	MJ NCV	1030	1.03	0.0757	2.56	9.69
Primary energy, renewable	MJ	293	0.293	0.0215	0.727	2.75
Acidification	kg SO2 eq.	0.226	0.000226	0.0000166	0.000561	0.00212
Eutrophication	kg N eq.	0.00784	0.00000784	0.000000576	0.0000195	0.0000737
Smog formation	kg O3 eq.	2.63	0.00263	0.000193	0.00653	0.0247
Particulate matter	kg PM2.5 eq.	0.0233	0.0000233	0.00000171	0.0000578	0.000219
Water consumption (excl. turbined water)	kg	183	0.183	0.0135	0.456	1.73

Table 4-4. Cradle-to-grave results for various conversions

Indicator	Unit	One thousand (1,000) cans	One (1) can	One (1) ounce of beverage	One (1) liter of beverage	One (1) gallon of beverage
Global warming	kg CO2 eq.	96.8	0.0968	0.00712	0.241	0.911
Primary energy, total	MJ	1630	1.63	0.12	4.06	15.4
Primary energy, fossil	MJ NCV	1210	1.21	0.089	3.01	11.4
Primary energy, renewable	MJ	421	0.421	0.031	1.05	3.97
Acidification	kg SO2 eq.	0.319	0.000319	0.0000235	0.000795	0.00301
Eutrophication	kg N eq.	0.00995	0.00000995	0.000000732	0.0000248	0.0000937
Smog formation	kg O3 eq.	3.41	0.00341	0.000251	0.00849	0.0321
Particulate matter	kg PM2.5 eq.	0.0338	0.0000338	0.00000249	0.0000842	0.000319
Water consumption (excl. turbined water)	kg	200	0.2	0.0147	0.497	1.88

4.2. Sensitivity Analysis

For this study, two analyses were conducted to test the sensitivity of the results towards variations in parameter values. It is meant to test one parameter at a time, while others remain constant. These parameters are tested based on assumptions. The sensitivity analysis is expressed as a percentage change in impact over a percentage change in parameter value to make sensitivities more comparable across different parameters.

4.2.1. Cradle-to-Gate Primary Aluminum Content

Figure 4-4 and Figure 4-5 show the cradle-to-gate results of the sensitivity analysis on PED and GWP. Overall, PED and GWP impacts go up as the percentage of primary aluminum increases from 0% to 100%. The base case primary aluminum percentage is 26.6%. In Figure 4-4, the linear slope is 22.7 MJ/% primary aluminum – the slope shows the steady increase of PED as the percentage of primary aluminum increases. In Figure 4-5, the linear slope is 1.43 kg CO2e/ % primary aluminum – the slope shows the steady increase of GWP as the percentage of primary aluminum increases. Numerical results of the sensitivity analysis are presented in Annex B.

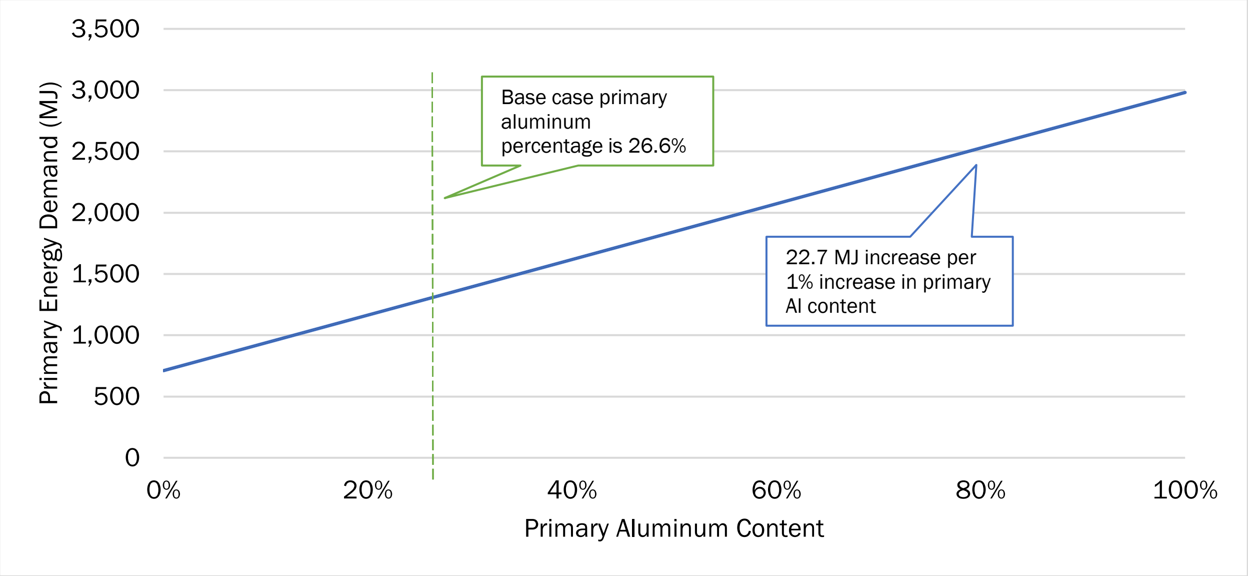


Figure 4-4: Effect of primary aluminum content on Primary Energy Demand

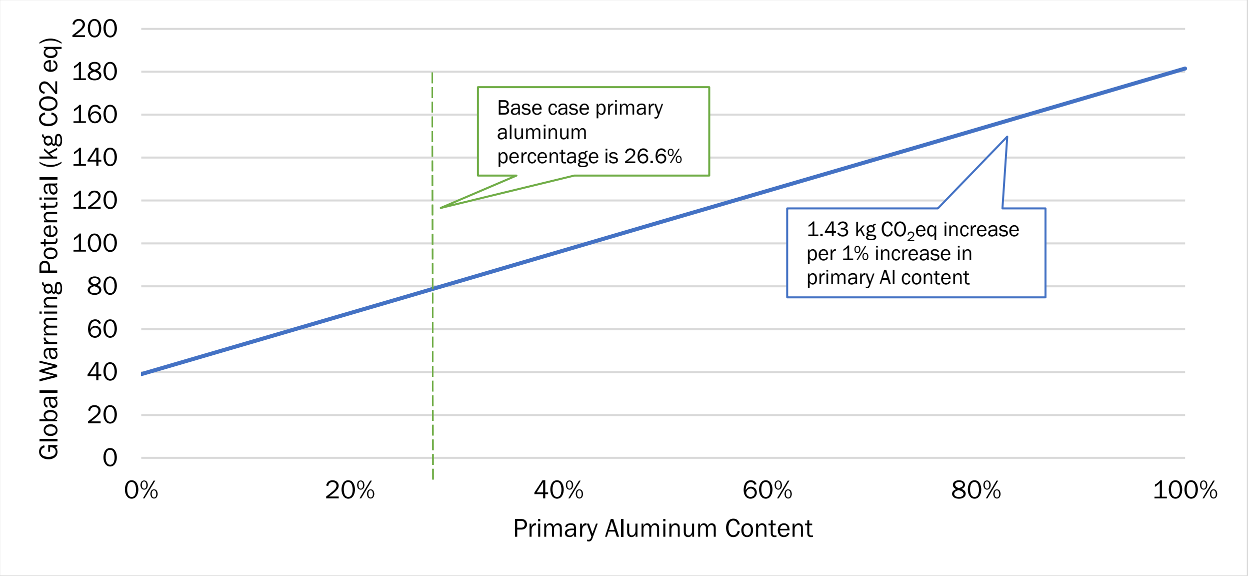


Figure 4-5: Effect of primary aluminum content on Global Warming Potential

4.2.2. Cradle-to-Grave End-of-Life Recycling

Figure 4-6 and Figure 4-7 show the cradle-to-grave results of the effects of UBC EoL recycling rate on PED and GWP. Overall, PED and GWP impacts go down as the recycling rate increases from 0% to 100%. The base case recycling rate is 50.4%. In Figure 4-6, the linear slope is -16.2 MJ/% recycling rate – the slope shows the steady decrease of PED as the recycling rate increases. In Figure 4-7, the linear slope is -1.02 kg CO2e/ % recycling rate – the slope shows the steady decrease of GWP as the recycling rate increases. Numerical results of the sensitivity analysis are presented in Annex B.

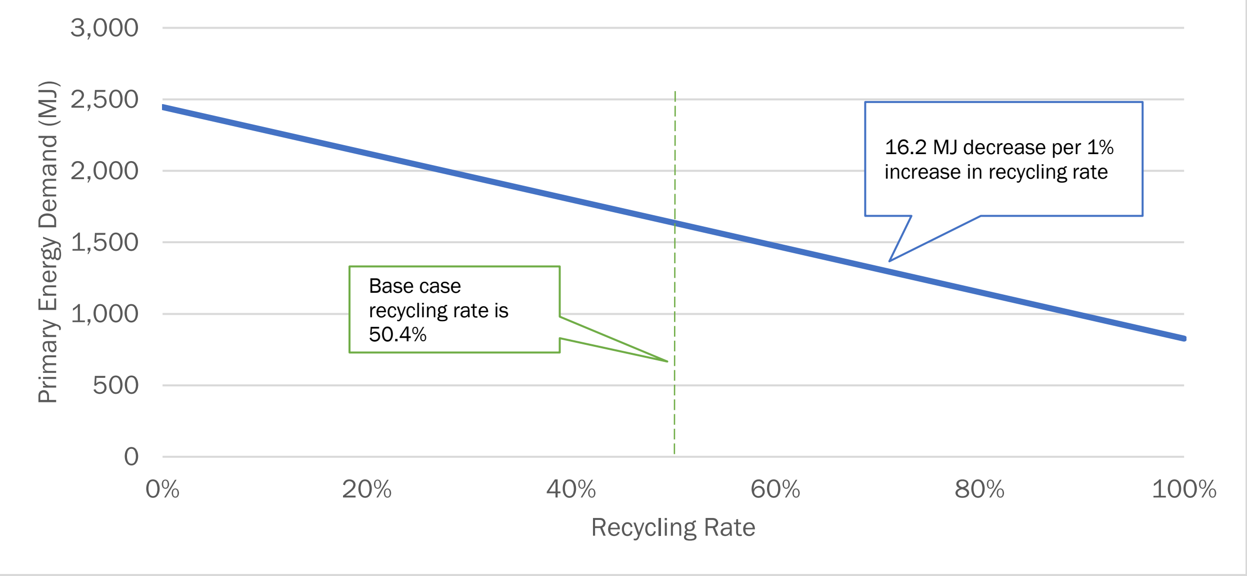


Figure 4-6: Effect of EoL recycling rate on Primary Energy Demand

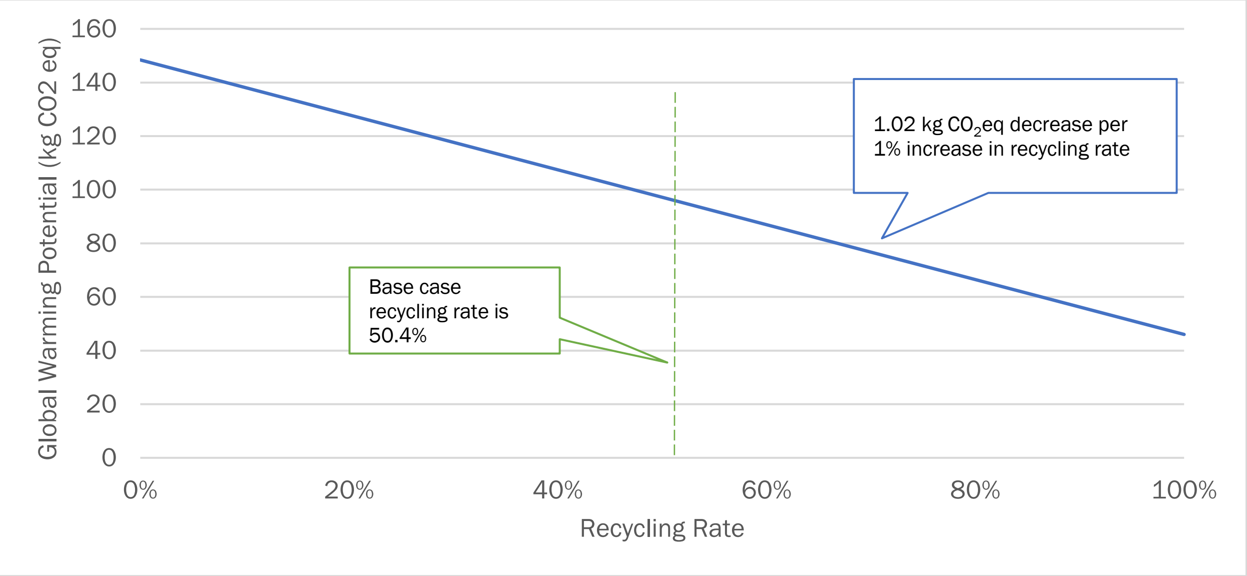


Figure 4-7: Effect of EoL recycling rate on Global Warming Potential

4.3. Scenario Analysis

Unlike the sensitivity analyses, the scenario analyses compare the results between discrete sets of parameter settings or normative model choices. In this case, the analyses compare results of the effects of aluminum sourcing.

4.3.1. Cradle-to-Gate Primary Aluminum Sourcing

The following analysis considers at the effect of sourcing primary aluminum from North America (base case – consumption mix), Canada, China, or the Middle East on the cradle-to-gate results. The percentage of primary metal in the cans is kept unchanged at 26.6% for the analysis. The consideration for including additional countries and regions in the scenario analysis is that primary aluminum produced in different countries and regions has unique characteristics. As shown in Table 4-5, primary aluminum produced in Canada, which is also part of North American domestic production, is using entirely hydropower as an electricity source. In contrast, primary metal produced in China is largely based on coal-fired power and Middle East is largely based on natural gas fired power.

Table 4-5. 2015 electricity consumption for regional aluminum production

	Unit	North America	Canada	China	Middle East
Hydro	GWh	49,543	40,456	42,602	0
Coal	GWh	16,284	0	383,422	0
Oil	GWh	1	0	0	0
Natural Gas	GWh	582	0	0	63,269
Nuclear	GWh	648	0	0	0
Total	**GWh**	**67,058**	**40,456**	**426,024**	**63,269**

Figure 4-8 and Figure 4-9 show the results of the scenario analysis on primary energy demand and global warming potential. As expected, sourcing primary aluminum from China or the Middle East shows the highest PED and GWP results. In particular, using primary aluminum produced in China to make a can with the same primary metal content (26.6%) would more than doubled the cradle-to-gate carbon footprint of the can as compared to a can using primary aluminum produced in Canada. It is also clear that sourcing aluminum from North America and Canada leads to similar results as most of the primary aluminum in North America is produced in Canada. Canada by itself is the region with the lowest PED and GWP due to its hydropower use for smelting.

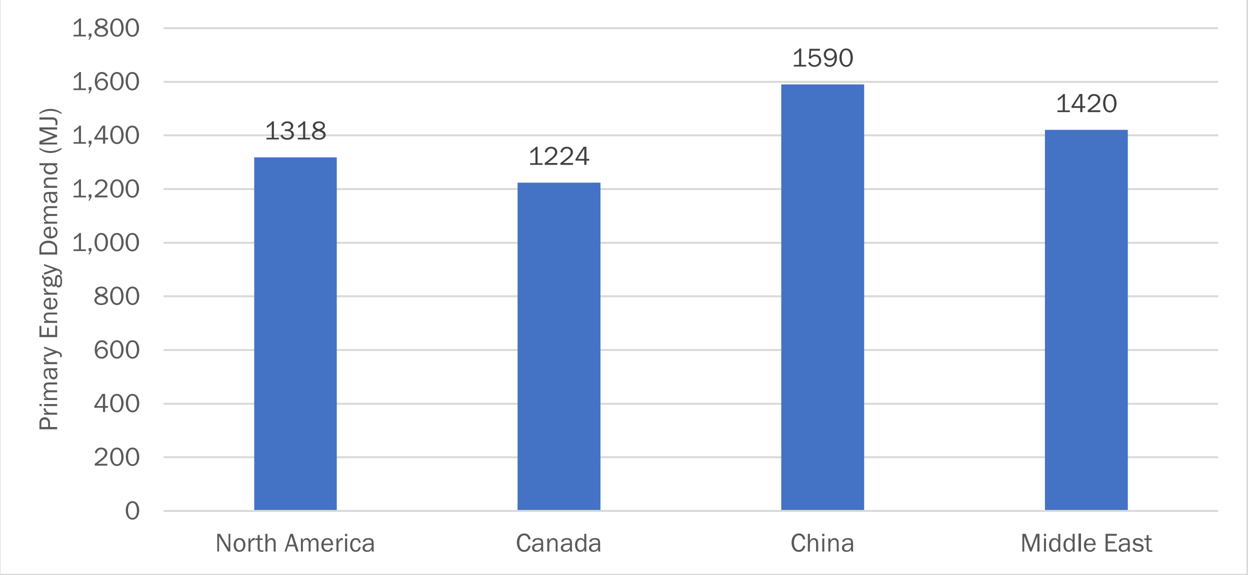


Figure 4-8: Effect of primary aluminum sourcing on cradle-to-gate Primary Energy Demand

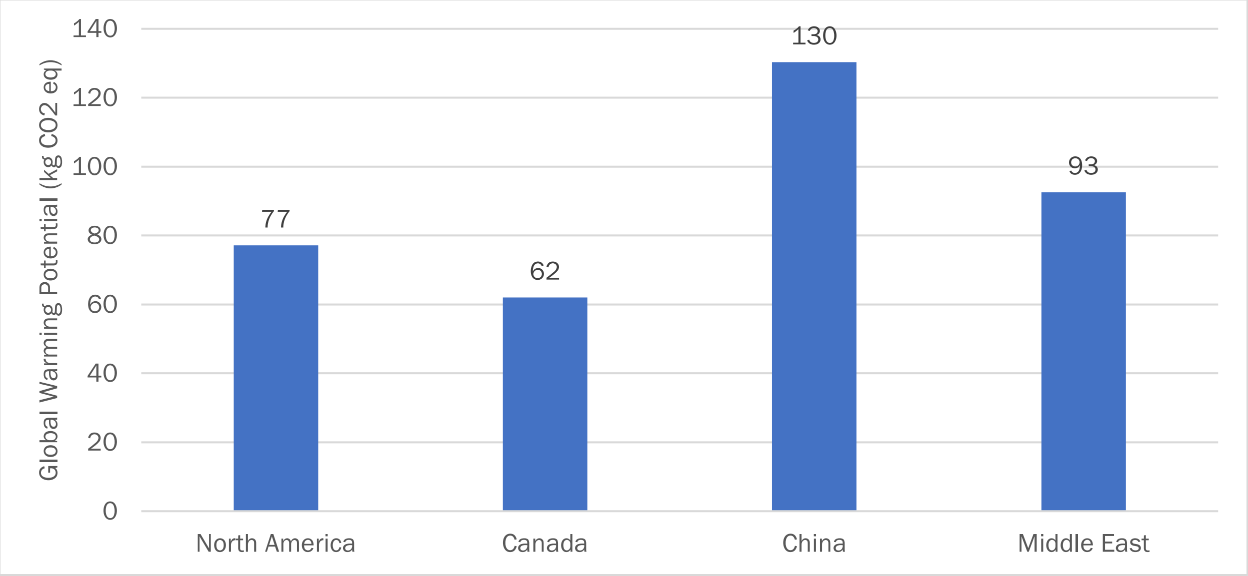


Figure 4-9: Effect of primary aluminum sourcing on cradle-to-gate Global Warming Potential

4.3.2. Cradle-to-Grave Best- and Worst-Case Scenarios

The second scenario analysis shows the effect of best- and worst-case scenarios on PED and GWP compared to the base case. The worst case assumes using 100% primary aluminum with 0% recycled content from China while the best case assumes using 100% secondary aluminum with 0% primary aluminum produced in North America. Results for this scenario analysis are presented in Figure 4-10 and Figure 4-11. As can be seen, when 100% recycling is achieved, the carbon footprint is only about 42kg.

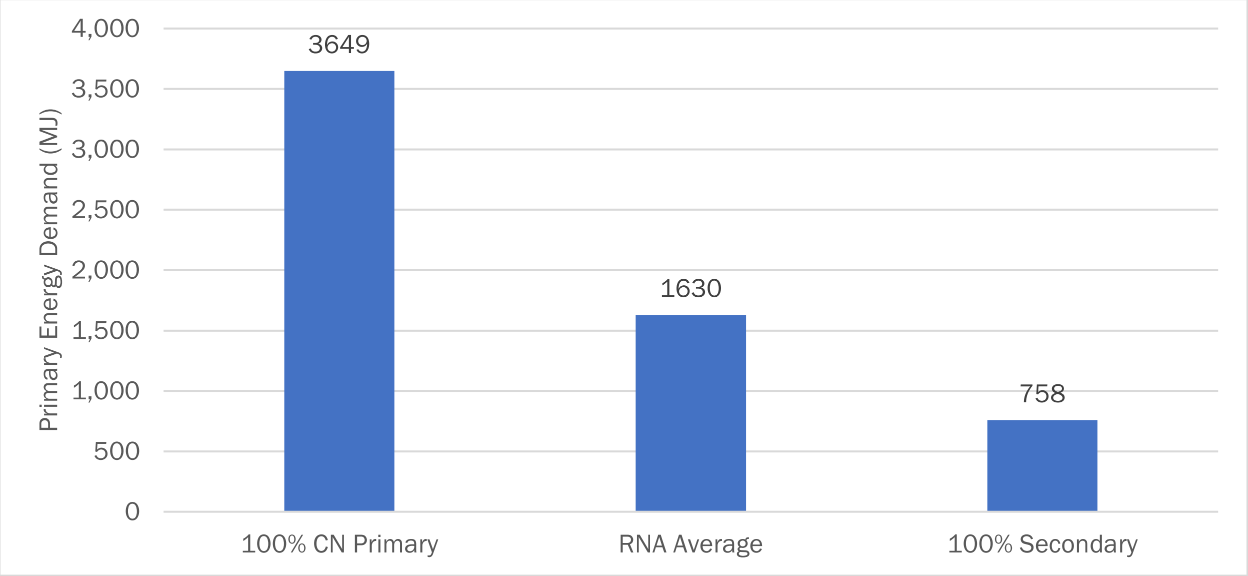


Figure 4-10: Effect of best- and worst-case on cradle-to-grave Primary Energy Demand

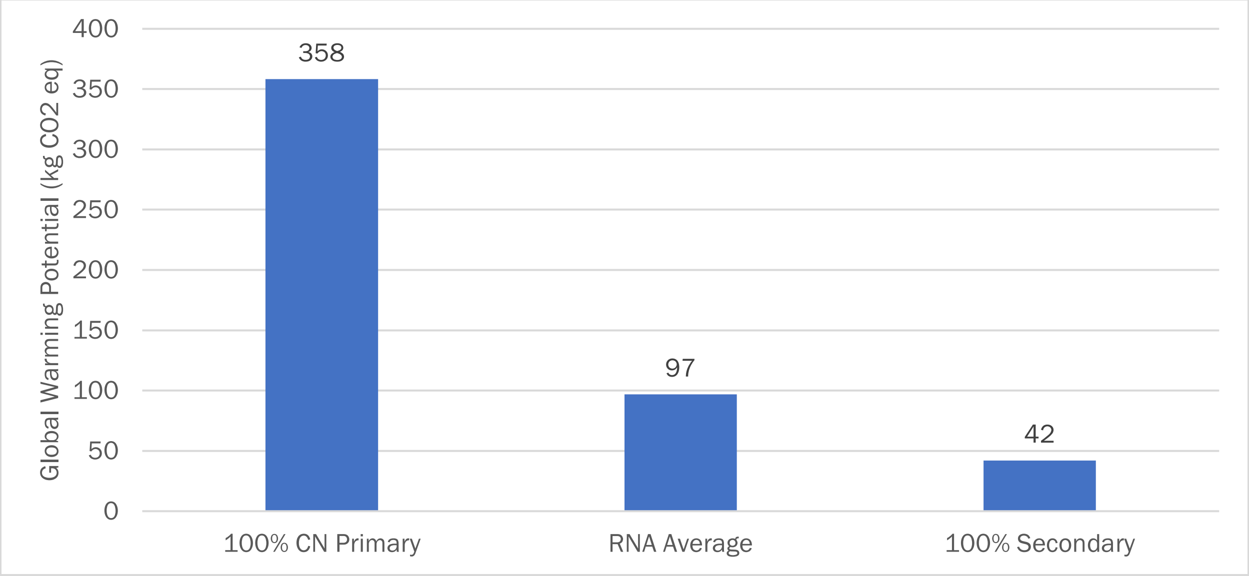


Figure 4-11: Effect of best- and worst-case on cradle-to-grave Global Warming Potential

5. Interpretation

5.1. Identification of Relevant Findings

This study has highlighted the overall impacts of aluminum beverage can production on PED and GWP. In both cradle-to-gate and cradle-to-grave scenarios, primary ingot and can manufacturing were the greatest contributors. In the cradle-to-gate scenario, primary ingot contributed 46% to the overall PED and 50% to the overall GWP. Can manufacturing also contributed 32% to the overall PED and 30% to the overall GWP. Together, primary ingot and can manufacturing represent 79% (1,040 MJ) of the total primary energy demand and a total of 80% of total global warming potential (61.8 kg CO2 eq.).

In addition to the contributions of primary ingot and can manufacturing, the cradle-to-grave scenario also daylights impacts from "crediting" of recycling at EoL. For cradle-to-grave results, primary ingot contributed 38% to overall PED and 40% to overall GWP. Can manufacturing contributed 26% to PED and 24% to GWP. The burden of supplementing net scrap deficit with primary ingot at end-of-life contributed 20% to overall PED and 22% to overall GWP. Concerning the end-of-life considerations, the results of this study indicate that raw material extraction and can manufacturing represent 64% of the total primary energy demand (1,040 MJ per 1,000 cans) and 64% of the total of global warming potential (61.8 kg CO2 eq).

5.2. Assumptions

The most important assumptions made for this study are related to the sourcing of raw materials. Primary aluminum, recycled aluminum and aluminum scrap are the major raw materials for can making. Given the fact that recycled aluminum is also made of aluminum scrap, the raw materials can be narrowed down to primary metal and scrap.

For primary aluminum, this study assumes that sourcing mirrors the entire semi-fabrication industry in the United States and Canada. In other words, no specific sourcing information was collected for can production. This treatment is consistent with all other LCAs done by the Aluminum Association. This is because there are legal barriers and confidentiality concerns related to tracking the supply chains of individual companies and specific market sectors by a trade association. As such, a primary aluminum consumption mix, represented by a production-weighted and country-specific supply for the entire North American market, was used to model the primary metal. In 2016, the majority of primary metal was supplied by North American domestic production and a small fraction was imported from Russia, the Middle East, South America, and the rest of the world. It is worth emphasizing that the source of importing countries and their relative shares of supply have been relatively stable during the past two decades. North America has not imported primary aluminum from China during the past 10 years and it is unlikely to do so in the near future.

For the supplying countries, electricity consumption for smelting is modeled based on that country's aluminum smelting electricity mix, which is surveyed and published by IAI. In addition, transportation distances of primary aluminum are also modeled accordingly by source countries.

For aluminum scrap, sourcing is assumed to be largely from North American domestic sources. Scrap is categorized as both pre-consumer and post-consumer scrap. Pre-consumer scrap comes mostly from can manufacturing facilities, which are usually located close in proximity to can sheet production facilities. Post-consumer scrap is mainly in the form of UBCs, with a small fraction from the building or other sectors. The majority of UBCs are generated and collected in the North American domestic market. A small fraction of UBCs is imported, mainly from Mexico and South America. Transportation of aluminum scrap from generation points to can sheet producer facilities are modeled accordingly.

5.3. Results of Sensitivity and Scenario Analysis

5.3.1. Sensitivity Analysis

Sensitivity analyses were performed to test the sensitivity of the results towards changes in parameter values that are based on assumptions or are otherwise uncertain or could be changed from production year to year (e.g., recycled content and EOL recycling rate). The parameters analyzed in this report belong to the last category. The analysis was done for both cradle-to-gate and cradle-to-grave scenarios. The cradle-to-gate results showed that overall PED and GWP impacts increase as the percentage of primary aluminum increases from 0% to 100%. The cradle-to-grave results show the overall PED and GWP impacts decrease as the recycling rate increases from 0% to 100%.

It is likely that the recycled content of the can would increase further as the UBC recycling rate increases under the assumption that more UBC scrap will be available in the market for can making; however, there are other market forces (e.g., export of UBC scrap to other countries, use of UBC scrap for automotive sheet production) that determine the recycled content of the can in the United States beyond the scope of this study.

5.3.2. Scenario Analysis

Scenario analyses were performed to compare results between different sets of assumptions or modeling choices. The analyses were done for both cradle-to-gate and cradle-to-grave scenarios. The cradle-to-gate analysis shows the sourcing of primary aluminum from North America, Canada, China and the Middle East. Overall, primary aluminum from China and the Middle East have the highest contributions on PED and GWP. The cradle-to-grave analysis depicts the best- (100% secondary aluminum from North America, 100% recycling rate) and worst-case scenarios (100% primary aluminum from China, 0% recycling rate). The results showed that the 100% secondary aluminum from North America results in the lowest PED and GWP for aluminum beverage cans. An opportunity exists to further improve the environmental footprint of aluminum beverage cans by increasing the secondary aluminum content of the can.

5.4. Data Quality and Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent background LCA information from the GaBi 2020 database were used. The LCI datasets from the GaBi 2020 database are widely distributed and used with the GaBi 10 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

5.4.1. Precision and Completeness

- ✓ **Precision:** As the majority of the relevant foreground data are measured data or calculated based on primary information sources of the owner of the technology, precision is considered to be high. All background data are sourced from GaBi databases with the documented precision.
- ✓ **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. No data were knowingly omitted. Completeness of foreground unit process data is considered to be high. All background data are sourced from GaBi databases with the documented completeness.

5.4.2. Consistency and Reproducibility

- ✓ **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail, while all background data were sourced from the GaBi databases.
- ✓ **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modeling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modeling approaches.

5.4.3. Representativeness

- ✓ **Temporal:** All primary data were collected for the year 2016. All secondary data come from the GaBi 2020 databases and are representative of the years 2010-2019. As the study intended to compare the product systems for the reference year 2016, temporal representativeness is considered to be high.
- ✓ **Geographical:** All primary and secondary data were collected specific to the countries or regions under study. Where country-specific or region-specific data were unavailable, proxy data were used. Geographical representativeness is considered to be high.
- ✓ **Technological:** All primary and secondary data were modeled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. Technological representativeness is considered to be high.

5.5. Model Completeness and Consistency

5.5.1. Completeness

All relevant process steps for each product system were considered and modeled to represent each specific situation. The process chain is considered sufficiently complete and detailed with regard to the goal and scope of this study.

5.5.2. Consistency

All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimized by exclusively using LCI data from the GaBi 2020 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

5.6. Conclusions, Limitations, and Recommendations

5.6.1. Conclusions

The study provides the Aluminum Association and its member companies with an updated LCI and LCIA of aluminum beverage can production in North America. The system boundary of this life cycle assessment for beverage cans includes primary aluminum production, secondary aluminum production, aluminum can sheet production, can manufacturing, and recycling of UBC.

The study showed that despite a high recycled content of 73%, the primary aluminum ingot remains the primary driver of environmental impacts. This is further aggravated by the low end-of-life recycling rate, which leads to the addition of primary aluminum burden in the end-of-life phase due to the net scrap deficit of the product system. Increasing the end-of-life recycling rate is therefore an effective way to reduce the cradle-to-grave environmental burdens of North American aluminum cans.

When putting this study in a historical context to benchmark the progress made by the industry in reducing the environmental footprint of beverage cans over the years, as seen in Figure ES-5, the cradle-to-grave carbon footprint of aluminum cans has declined by 43% since 1991. Reduction in primary energy demand is in a similar range (Figure ES-6). Much of the progress is attributable to the following:

- The metallic weight of an average can has declined by 18% from 15.83 grams to 12.99 grams, and 27% from 1.32 grams per fluid ounce to 0.96 grams per fluid ounce;
- The environmental footprint of primary aluminum production in North America has been significantly reduced; and
- The manufacturing processes along the entire value chain have become far more efficient.

Focusing on two of the most frequently cited assessment parameters – Primary Energy Demand (PED) and Global Warming Potential (GWP, commonly called carbon footprint) – the study has reached the following conclusions:

- The **cradle-to-gate** PED and GWP for 1,000 cans, from raw material extraction to the point in which an empty beverage can is made, painted and sealed, are 1,320 MJ LHV and 77.1 kg CO_2 equivalents, respectively.
- The **cradle-to-grave** PED and GWP for 1,000 cans, including end-of-life disposal and recycling, are 1,630 MJ LHV and 96.8 kg CO_2 equivalents, respectively.

Notably, the cradle-to-gate footprint is lower than the cradle-to-grave footprint. This is unusual for products that are fully recycled at the end of their useful life and receive a credit of primary production based on the amount of the recovered secondary material. In the specific case of aluminum cans made in North America, however, the EoL recycling rate is lower than the recycled content. Collecting less aluminum scrap in end-of-life recycling than what is consumed during production leads to a *net scrap deficit* of the product system, which burdens the product system and increases the PED and GWP of the beverage can over the full life cycle. Bringing back more aluminum cans through increased consumer recycling is therefore one of the key opportunities to reduce the environmental footprint of aluminum beverage cans in the future.

Unfortunately, the end-of-life recycling rate for aluminum cans has dropped more than 10 percentage points – from more than 62% in 1991 to around 50% today. This deterioration offsets a significant amount of positive progress achieved in other areas over the years. The Aluminum Association advocates for many policies to increase the quality and quantity of used aluminum beverage cans coming back into the system. But increasing recycling in a meaningful way will require a wider effort involving hundreds of millions of individuals and stakeholders.

5.6.2. Limitations

The study represents the life cycle of aluminum cans made and consumed in North America in the reference year 2016. The results cannot be generalized beyond this scope and do not represent aluminum cans made in other regions of the world. Cradle-to-grave results depend directly on the recycled content of the aluminum cans, the electricity grid mix used for primary aluminum smelting and the end-of-life recycling rate, all of which are subject to change depending on the reference region, reference period, and value choices made by the practitioner and commissioner of the study.

5.6.3. Recommendations

Overall, it is not to be expected that a fully recycled product at the end of life has greater impacts than a cradle-to-gate scenario; however, seeing as there is a significant loss of aluminum at the end-of-life due to recycling rate being lower than the amount of recycled content in the can, there is not enough secondary material being produced to manufacture a product with a high percentage of secondary aluminum. It is known that primary ingot is the greatest contributor to overall PED and GWP. Though reducing the amount of primary ingot in cans will significantly improve results, one of the root causes of the use of so much primary ingot is due to a low recycling rate. If recycling rate is improved, the need for primary ingot can be reduced.

Performing a deeper analysis on the EoL recycling process and rate can help uncover where and why the recycling rate is so low. A more detailed understanding of recycling rate can help uncover a solution so that there is a better balance between recycling rate and recycled content. Greater availability of recycled content will drive a decrease in primary ingot use and reduce overall impacts in both cradle-to-gate and cradle-to-grave scenarios.

References

Aluminum Association. (2020). *The Aluminum Can Advantage - Sustainability Key Performance Indicators.*

Bare, J. (2012). *Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) - Software Name and Version Number: TRACI version 2.1 - User's Manual.* Washington, D.C.: U.S. EPA.

Drielsmaa, J., Russell-Vacari, A., Drnek, T., Brady, T., Weihed, P., Mistry, M., & Perez Simbor, L. (2016). Mineral resources in life cycle impact assessment—defining the path forward. *International Journal of Life Cycle Assessment*, 85-105.

EPA. (2012). *Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) – User's Manual.* Washington, D.C.: U.S. EPA.

Graedel, T., & Reck, B. (2015). Six Years of Criticality Assessments - What Have We Learned So Far? *Journal of Industrial Ecology*. doi:10.1111/jiec.12305

Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., . . . Huijbregts, M. (2002). *Handbook on life cycle assessment. Operational guide to the ISO standards.* Dordrecht: Kluwer.

IPCC. (2013). *Climate Change 2013: The Physical Science Basis.* Genf, Schweiz: IPCC.

ISO. (2006). *ISO 14040/Amd.1:2020: Environmental management – Life cycle assessment – Principles and framework.* Geneva: International Organization for Standardization.

ISO. (2006). *ISO 14044:2006/Amd.1:2017/Amd.2:2020 Environmental management – Life cycle assessment – Requirements and guidelines.* Geneva: International Organization for Standardization.

Koffler, C., & Finkbeiner, M. (2017). Are we still keeping it "real"? Proposing a revised paradigm for recycling credits in attributional life cycle assessment. *Int J Life Cycle Assess, 23*, 181-190. doi:https://doi.org/10.1007/s11367-017-1404-x

Nassar, N., Barr, R., Browning, M., Diao, Z., Friedlander, E., Harper, E., . . . Graedel, T. (2012). Criticality of the Geological Copper Family. *Environmental Science & Technology*, 1071-1078.

Pfister, S., Koehler, A., & Hellweg, S. (2009). Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environ. Sci. Technol., 43(11)*, 4098–4104.

Rosenbaum, R. K., Bachmann, T. M., Swirsky Gold, L., Huijbregts, M., Jolliet, O., Juraske, R., . . . Hauschild, M. Z. (2008). USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int J Life Cycle Assess, 13(7)*, 532–546.

Sphera. (2020). *GaBi LCA Database Documentation*. Retrieved from Sphera Solutions, Inc.: http://www.gabi-software.com/america/support/gabi/

WHO. (2021, Feb 21). *Health Impacts*. Retrieved from https://www.who.int/teams/environment-climate-change-and-health/air-quality-and-health/transport/health-impacts worldsteel. (2017). *Life Cycle Inventory Methodology Report.* Brussels: World Steel Association. Retrieved Feb 21, 2021, from https://www.worldsteel.org/en/dam/jcr:6eefabf4-f562-4868-b919-f232280fd8b9/LCI%2520methodology%2520report_2017.pdf

Annex A. Critical Review Statement

Industrial Ecology Consultants

May 24, 2021

Critical Review Report: Life Cycle Assessment of North American Aluminum Cans

The LCA Practitioner, Sphera commissioned a Life Cycle Assessment (LCA) expert to perform an external independent critical review of the **Life Cycle Assessment of North American Aluminum Cans.** Sphera completed the LCA study on behalf of the commissioning organization, The Aluminum Association.

The review of the study was performed to demonstrate conformance with the following standards:

> International Organization for Standardization. (2020). *Environmental management -- Life cycle assessment – Principles and framework* (ISO 14040:2006/AMD 1:2020).
>
> International Organization for Standardization. (2020). *Environmental management -- Life cycle assessment -- Requirements and guidelines* (ISO 14044:2006/AMD 2:2020).
>
> International Organization for Standardization. (2014). *Environmental management -- Life cycle assessment -- Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044*. (ISO/TS 14071:2014).

The independent third-party critical review was conducted by the following expert per ISO 14044:2006 Section 6.2: Critical review:

Thomas P. Gloria, Ph.D.
Founder, Chief Sustainability Engineer
Industrial Ecology Consultants

REVIEW SCOPE

The intent of this review was to provide an independent third-party external critical review of a LCA study report in conformance with the aforementioned ISO standards. This review did not include an assessment of the Life Cycle Inventory (LCI) model, however, it did include a detailed analysis of the individual datasets used to complete the study.

REVIEW PROCESS

The review process involved the critical assessment of all requirements set forth by the applicable ISO standards cataloged in comprehensive review table along with editorial comments. There was one round of comments by the reviewer submitted to the LCA practitioner. Responses by the LCA practitioner to each issue raised were resolved and acknowledged by the reviewer to have been satisfactorily addressed.

Industrial Ecology Consultants

CRITICAL REVIEW STATEMENT

Based on the review objectives, the **Life Cycle Assessment of North American Aluminum Cans, May 19, 2021** was determined to be ***in conformance*** with the applicable ISO standards. The plausibility, quality, and accuracy of the LCA-based data and supporting information are confirmed.

As the external independent third-party reviewer, I confirm that I have sufficient scientific knowledge and experience of non-ferrous metals and the applicable ISO standards to carry out this review.

Sincerely,

Thomas P. Gloria, Ph.D.
Founder, Chief Sustainability Engineer
Industrial Ecology Consultants

Annex B. Detailed Results

Annex B1: Water Consumption Results, Including Turbined Water

Table B-1: Water consumption results, including turbined water, per 1,000 cans under cut-off approach (cradle-to-gate)

Indicator	Unit	Primary Ingot	Re-melting and casting	Can sheet rolling	Can manufacturing	Total
Water consumption (incl. turbined water)	kg	790	3.09	23.1	181	**1,000**

Table B-2: Water consumption results, including turbined water, per 1,000 cans under closed loop approach (cradle-to-grave)

Type	Unit	Primary Ingot	Re-melting and casting	Can sheet rolling	Can manufacturing	UBC EoL Burden	UBC EoL Credit	Total
Water consumption (incl. turbined water)	kg	790	3.09	23.1	181	-7.37	430	**1,420**

Annex B2: Sensitivity Analysis Results

Table B-3: Effect of primary aluminum content on PED and GWP (cradle-to-gate)

Indicator	Unit	0%	25%	50%	75%	100%
Global warming	kg CO_2 eq.	39.0	74.6	110	146	182
Primary energy, fossil	MJ NCV	711	1,280	1.850	2,410	2,980

Table B-4: Effect of EoL recycling rate on PED and GWP (cradle-to-grave)

Indicator	Unit	0%	50%	100%
Global warming	kg CO_2 eq.	148	97.2	46.0
Primary energy, fossil	MJ NCV	2,450	1,640	738

Annex B3: Scenario Analysis Results

Table B-5: Effect of primary aluminum sourcing on PED and GWP (cradle-to-gate)

Indicator	Unit	RNA	CA	CN	RME
Global warming	kg CO_2 eq.	77.1	62.0	130	92.5

Indicator	Unit	RNA	CA	CN	RME
Primary energy, fossil	MJ NCV	1,320	1,220	1,590	1,420

Table B-6: Effect of best- and worst-case on PED and GWP (cradle-to-grave)

Indicator	Unit	100% CN Primary	RNA Average	100% Secondary
Global warming	kg CO_2 eq.	358	96.8	42.0
Primary energy, fossil	MJ NCV	3,650	1,630	758