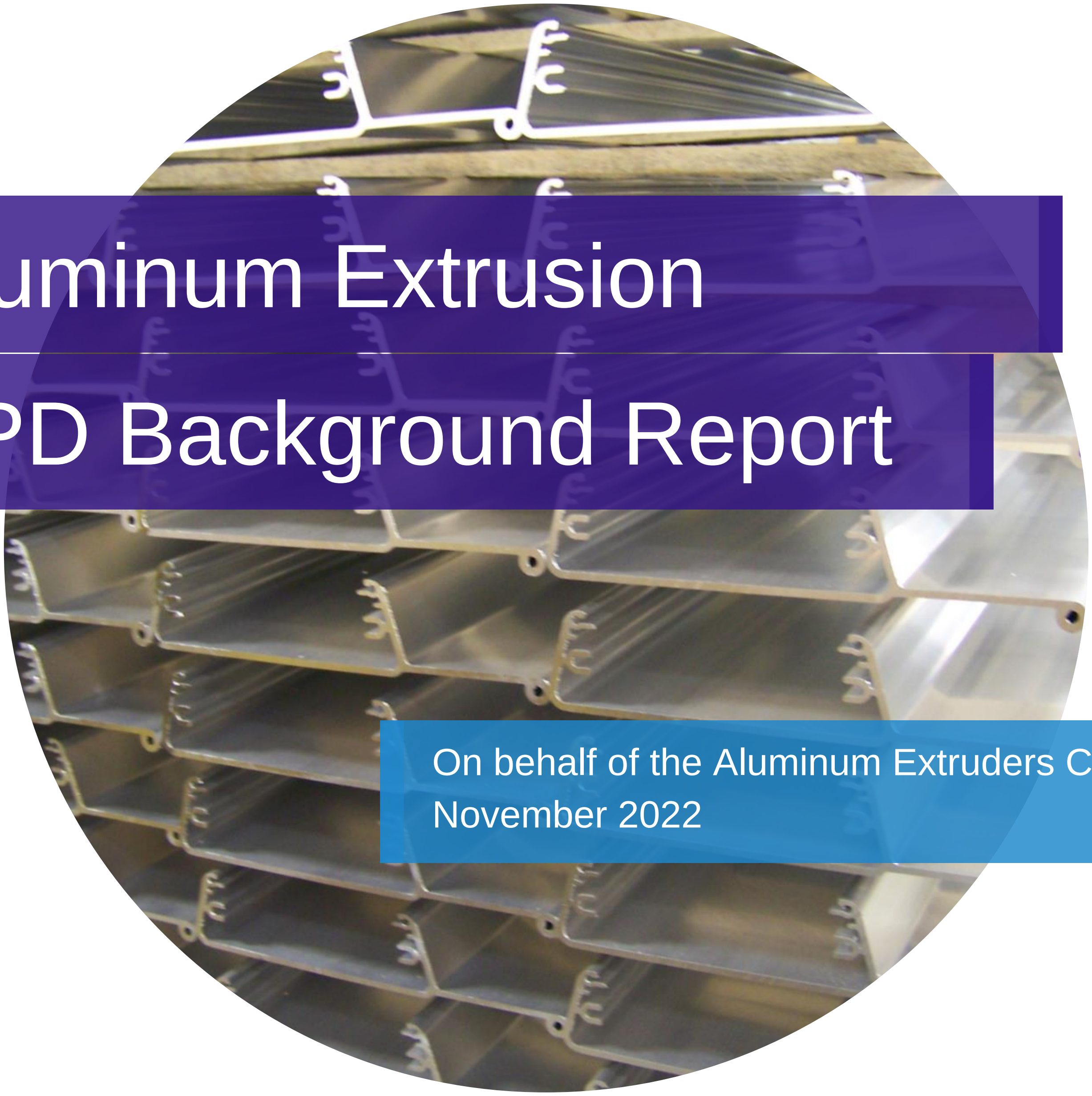

# Aluminum Extrusion

# EPD Background Report

On behalf of the Aluminum Extruders Council
November 2022

| | |
|---|---|
| Client: | **Aluminum Extruders Council** |
| Title: | **EPD Background Report: Cradle-to-Gate Assessment for Aluminum Extrusions** |
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## On behalf of Sphera Solutions, Inc. and its subsidiaries

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If you have any suggestions, complaints, or any other feedback, please contact us at servicequality@Sphera.com.

# Table of Contents

# List of Figures

# List of Tables

# List of Acronyms

| | |
|---|---|
| AA | Aluminum Association |
| ADP | Abiotic Depletion Potential |
| AEC | Aluminum Extruders Council |
| AP | Acidification Potential |
| CML | Centrum voor Milikunde Leiden |
| EoL | End-of-Life |
| EPA | (United States) Environmental Protection Agency |
| EP | Eutrophication Potential |
| EPD | Environmental Product Declaration |
| GaBi | Ganzheitliche Bilanzierung (German for holistic balancing) |
| 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 |
| NMVOC | Non-Methane Volatile Organic Compound |
| ODP | Ozone Depletion Potential |
| PCR | Product Category Rules |
| SDS | Safety Data Sheet |
| SFP | Smog Formation Potential |
| TDS | Technical Data Sheet |
| TRACI | Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts |

# Glossary

*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)

*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.

*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)

*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).

*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.

*Functional unit*

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

*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)

# 1. Goal of the Study

The Aluminum Extruders Council (AEC), formed over 70 years ago, is the trade association for the North American aluminum extrusion industry. With approximately 60 U.S. and Canadian extruder members (operating over 100 extrusion manufacturing locations) and a similar number of aluminum producers and other industry suppliers, AEC members represent an estimated 75% of North American aluminum extrusion production.

Today, AEC focuses on four distinct missions:

1. Promoting the effective application of aluminum extrusions to solve product challenges in a wide range of industries. Whether helping create more energy efficient buildings, improving automotive performance, facilitating the transition to LED lighting, or advancing products in a wide range of other industries, extrusions are playing a major role.
2. Advancing extrusion technology sustainability and competence, via member training, networking, benchmarking, best-practice sharing and research & development projects and conferences.
3. Ensuring fair trade.
4. Developing the human capital required for the coming years via apprentice programs, upskilling, and collaboration with educational institutions and workforce development programs

The goal of the study is to create two industry average Environmental Product Declarations (EPDs): one for mill finished, anodized, or painted aluminum extrusions, and a second for thermally improved aluminum extrusions (anodized and painted). Analyses were conducted in accordance with the International Standard ISO 14044. The LCA report and final EPDs conform with ISO 14025, ISO 21930, and ISO 14044 standards and will enable AEC to provide EPDs to their customers.

The goal and scope of the LCA were informed by the *Product Category Rule (PCR) for Aluminum Construction Products* published by UL Environment (ULE) which describes the format and requirements for creating an EPD for aluminum and aluminum alloy products in the construction industry (ULE, 2022).

The intended audience for this report includes the program operator, UL Environment (ULE), as well as the verifier who will be assessing the conformance of the life cycle assessment (LCA) to the chosen PCR. The audience further includes AEC and its participating member companies. To foster further transparency, Sphera recommends that this report be made available upon request to all third parties to whom the EPD is provided. Company-specific information has been aggregated to create a production volume weighted industry average based on product mass; therefore, confidential information specific to each company is not disclosed in this report.

Results presented in this document do not constitute comparative assertions. However, these results will be disclosed to the public via EPDs, which architects and builders will be able to use to compare AEC's products with similar products presented in other EPDs that follow the same PCR. To be published by a program operator, the EPD will undergo a verification for conformance to the PCR.

This study was commissioned by AEC and performed by Sphera, Inc. Conformance of the background LCA study as well as the final EPDs with the guiding PCR and with ISO 21930, ISO 14025, ISO 14040, and ISO 14044 was verified by ULE.

# 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

This declaration covers a range of aluminum extrusion products manufactured by AEC members in North America. The products considered in this declaration are as follows:

- Mill finished aluminum extrusion
- Painted aluminum extrusion
- Anodized aluminum extrusion
- Thermally improved, painted aluminum extrusion
- Thermally improved, anodized aluminum extrusion

While thermally improved mill finish extrusion may also be produced and sold, the incidence of this configuration is so low it precludes meaningful data, hence the Mill-finish thermally treated Aluminum extrusions are excluded in this report and the final EPD.

The information in this document is based on information supplied by 8 AEC member companies in the U.S. and Canada. The data comes from 31 separate production facilities, with a total of nearly 100 extrusion presses ranging in size from 6" to 18" circle size, 10 anodizing facilities, 10 paint facilities (liquid and powder), 6 thermal management operations, and 13 cast houses that produce scrap-based extrusion billets.
The participating AEC members and facilities under their operational control are shown in Table 2-1.

Total extrusion production by the AEC participants is 2.46 billion lbs which is 38% of the total Aluminum extrusions in North America for the 2020 production year (AA, 2022).

**Table 2-1: Participating AEC members and reported operations**

| Company | Extrusion | Anodizing | Painting | Thermal Improvement | Cast House |
|---|---|---|---|---|---|
| Almag Aluminum, Inc. | X | | | | |
| Apel Extrusions Limited | X | X | X | X | |
| Bonnell Aluminum | X | X | X | X | X |
| Hydro Extrusion N.A. | X | X | X | X | X |
| Keymark Aluminum | X | X | X | X | X |
| Pennex Aluminum Company, LLC | X | | | | X |
| Sierra Aluminum | X | X | X | X | X |
| Western Extrusions Corp. | X | X | X | X | |
| Number of Sites (Total) | 27 | 10 | 10 | 6 | 13 |

Aluminum extrusions in 6000 series alloy (the predominant alloy produced by the participants) are approximately 96.2% to 98.6% aluminum by mass, with alloying elements composing the remaining mass. The percent aluminum by mass of the painted, anodized, and thermally improved extrusions varies by less than 5% from this, and can be found in Table 3-5. Additional technical data can be found in Table 2-2.

**Table 2-2: Technical data for aluminum extrusions (6xxx alloy, tempers T1-T6)**

| Name | Value | Unit |
|---|---|---|
| Density | 2.66 – 2.84 | (kg/$m_3$) x $10_3$ |
| Melting point (typical) | 475 – 655 | °C |
| Electrical conductivity (typical) at 20°C / 68ºF | Equal volume: 16 – 36 | Ms/m (0.58 x %IACS) |
| Thermal conductivity (typical) at 25°C / 77°F | 170 – 210 | W/m·K |
| Average coefficient of thermal expansion (typical) 20°C to 100°C / 68°F to 212°F | 22.3 – 23.9 | per °C |
| Modulus of elasticity (typical) | 69 – 73 | MPa x $10_3$ |
| Hardness (typical) | 40 – 95 (47 – 96) | HB (Rockwell E) |
| Yield strength (min) | 60 – 330 | MPa |
| Ultimate tensile strength (min) | 120 – 370 | MPa |
| Breaking elongation (min) (50mm & 4D) | >4 | % |
| Chemical composition | Varying by alloy, Al 95.2 – 98.6 | % by mass |
| Density | 2.66 – 2.84 | (kg/$m_3$) x $10_3$ |
| Melting point (typical) | 475 – 655 | °C |

At the plants for each of the participating AEC members, the aluminum is extruded and then either anodized, painted, or left unfinished (mill finish). The finished aluminum is then either sold as is or a thermal break is applied. Downstream fabrication operations, such as tight-tolerance cutting, machining, and assembly, are excluded due to the wide diversity of such operations. Because of their many attributes and the variety of available finishing options, aluminum extrusions are useful in a myriad of products in various market sectors, including building and construction, transportation, electrical and energy, medical and consumer, machinery, military, and air. Some uses in these market sectors are as follows:

- **Building and construction:** windows, doors, curtain walls, façade systems, skylights, canopies, louvers, light shelves, interior partitions, bridges, etc.
- **Transportation:** automotive structural and chassis components, crash management systems, BEV battery enclosures, auto body and trim components, truck and trailer components, rail passenger and freight car components, etc.
- **Electrical and energy:** electronics housings and heat sinks, LED lighting components, solar energy mounting and racking systems, cable raceways, conduit, etc.
- **Medical and consumer durables:** components of recreation products, home & garden tools, appliances, ambulatory care products, medical diagnostic equipment, etc.

## 2.2. Declared Unit

The declared unit is ***one metric ton (1,000 kg) of extruded aluminum***, including the optional surface treatments described in section 2.1.

## 2.3. System Boundary

The scope of the study includes raw material sourcing and extraction, manufacturing, and end-of-life (EoL) disposal of aluminum extrusions, along with a substitution credit for recycling in future product systems. The included life cycle stages are summarized in Table 2-3 according to the EN 15804 standard referenced in the PCR.

**Table 2-3: Life cycle modules included in EPD**

| Production | | | Installation | | Use stage | | | | | | | End-of-Life | | | | Next product system |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Raw material supply (extraction, processing, | Transport to manufacturer | Manufacturing | Transport to building site | Installation into building | Use / application | Maintenance | Repair | Replacement | Refurbishment | Operational energy use | Operational water use | Deconstruction / demolition | Transport to EoL | Waste processing for reuse, recovery or recycling | Disposal | Reuse, recovery or recycling potential |
| A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
| X | X | X | MND | MND | MND | MND | MND | MND | MND | MND | MND | X | X | X | X | X |

*X = declared module; MND = module not declared*

**Table 2-4: System boundaries**

| Included | Excluded |
|---|---|
| ✓ Raw materials production (bauxite, chemicals, minerals, etc.) (A1)<br>✓ Upstream electricity generation for production (A1)<br>✓ Inbound transportation of raw materials (A2)<br>✓ Product manufacturing and packaging (A3)<br>✓ Use of auxiliary materials, water, and energy during manufacturing (A3)<br>✓ Emissions to air, water, and soil during manufacturing (A3)<br>✓ Disposal (C4) and recycling credits (D)<br>✓ Internal transportation (within a manufacturing facility) (A3)<br>✓ Deconstruction (C1), transport to EoL (C2), and waste processing (C3)<br>✓ Substitution credit for recycling in future product systems (D) | × Construction of capital equipment<br>× Maintenance and operation of support equipment (e.g., employee facilities, etc.)<br>× Packaging of raw materials<br>× Human labor and employee commute<br>× Fabrication (e.g., cutting, bending, welding)<br>× Transport of finished products to installation site (A4), and application of product (A5)<br>× Use stage (B1-B7) |

### 2.3.1. Time coverage

The data are intended to represent aluminum extrusion production during the calendar years 2020 to 2021. As such, each participating AEC member company provided primary data for 12 consecutive months for the year 2020 while one company reported for July 2020 to June 2021. These data were then used to calculate average production values for each company.

### 2.3.2. Technology coverage

This study is intended to be representative of the aluminum extrusion and associated finishing processes. All foreground data was collected from AEC members for their facilities and is intended to represent average extrusion and finishing technologies.

### 2.3.3. Geographical coverage

This background LCA represents AEC members' products produced in the U.S. and Canada. Background data are representative of these countries, with exceptions noted in Section 0.

Regionally specific datasets were used to represent each manufacturing location's electricity consumption, however, proxy datasets were also used as needed for raw material inputs to address lack of data for a specific material or for a specific geographical region. For some companies, some of the unit operations are partly in Canada and United states, in those cases U.S. electricity average grid mix dataset is used. These proxy datasets were chosen for their technological representativeness of the actual materials.

## 2.4. Allocation

### 2.4.1. Co-Product allocation

No co-product allocation occurs in the product foreground system. Allocation was used in the GaBi background data. For further information on a specific product see http://www.gabi-software.com/international/databases/gabi-databases/.

### 2.4.2. End-of-Life allocation

End-of-Life allocation generally follows the requirements of ISO 14044 and ISO 21930.

A closed loop recycling approach was used in this study. The EoL scrap destined for recycling was looped back into the system to provide the scrap material needed in Module A. The impacts and credits associated with the remaining "net scrap" are then reported in module D.

The net scrap approach is based on the perspective that material that is recycled into secondary material at end of life will replace an equivalent amount of virgin material. Hence a credit is given to account for this material substitution. A schematic of the Module D calculation is presented in Figure 2-1.

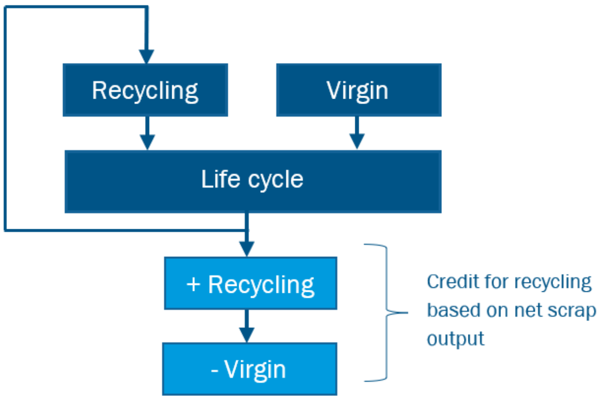


**Figure 2-1 Schematic for the net scrap approach (credit given at the end-of-life)**

## 2.5. Cut-off Criteria

In the case of data gaps for unit processes, the cut-off criteria as defined by ISO 21930 were applied. 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. No inputs constituting greater than 1% of mass input or energy usage were excluded from the study. The total flows cut off in this study never exceeded 5% of either the mass or energy usage in any one life cycle module.

The choice of proxy data is documented in Chapter 3, and the effects of using the proxy data on the results and conclusions are discussed in Chapter 5

## 2.6. Selection Of LCIA Methodology And Impact Categories

The life cycle impact assessment (LCIA) categories and other indicators considered to be of high relevance to the goals of the project are listed in this chapter. TRACI 2.1 (EPA, 2012), IPCC AR5 (IPCC, 2013)and CML-IA v4.8 (CML, 2016) impact assessment methodology frameworks are used for results reporting for this EPD. The impact assessment categories and other metrics required by the PCR are shown in Table 2-5. GWP excludes biogenic carbon as there are no relevant biogenic carbon removals or emissions in the life cycle. There is no calcination, carbonation, or combustion of waste from non-renewable sources.

**Table 2-5: Declared indicators of environmental impacts, use of resources, and generation of waste**

| Indicator | Unit | Methodology |
|---|---|---|
| **Life Cycle Impact Assessment Results** | | |
| Global warming potential, excluding biogenic carbon (GWP 100) | kg $CO_2$ eq | IPCC AR5 (IPCC, 2013) |
| Ozone depletion potential (ODP) | kg CFC-11 eq | TRACI 2.1<br>(Bare, 2012)<br>(EPA, 2012) |
| Acidification potential (AP) | kg $SO_2$ eq | |
| Eutrophication potential (EP) | kg N eq | |

| | | |
|---|---|---|
| Smog formation potential (SFP) | kg $O_3$ eq | |
| Abiotic depletion potential for fossil resources ($ADP_{fossil}$) | MJ LHV | CML-IA v4.8 (CML, 2016) |
| **Resource Use** | | |
| Renewable primary resources used as energy carrier (fuel) ($RPR_E$) | MJ LHV | ISO 21930 (ISO, 2017), informed by the ACLCA Guidance document (ACLCA, 2019) |
| Renewable primary resources with energy content used as material ($RPR_M$) | MJ LHV | |
| Non-renewable primary resources used as an energy carrier (fuel) ($NRPR_E$) | MJ LHV | |
| Non-renewable primary resources with energy content used as material ($NRPR_M$) | MJ LHV | |
| Secondary materials (SM) | kg | |
| Renewable secondary fuels (RSF) | MJ LHV | |
| Non-renewable secondary fuels (NRSF) | MJ LHV | |
| Recovered energy (RE) | MJ LHV | |
| Use of net fresh water resources (FW) | $m^3$ | |
| **Output Flows and Waste Categories** | | |
| Hazardous waste disposed (HWD) | kg | ISO 21930 (ISO, 2017), informed by the ACLCA Guidance document (ACLCA, 2019) |
| Non-hazardous waste disposed (NHWD) | kg | |
| High-level radioactive waste, conditioned, to final repository (HLRW) | kg | |
| Intermediate- and low-level radioactive waste, conditioned, to final repository (ILLRW) | kg | |
| Components for re-use (CRU) | kg | |
| Materials for recycling (MR) | kg | |
| Materials for energy recovery (MER) | kg | |
| Recovered energy exported from the product system (EE) | MJ LHV | |

It shall be noted that the above LCIA 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 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.
- 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. 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 2021 LCI database (CUP 2021.2) provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

## 2.10. Verification

The EPD development process requires verification by the selected program operator, UL Environment. Verifications were conducted in accordance with ISO 14025 and ISO 21930 requirements and the referenced PCR. The third-party review was provided by Thomas Gloria from Industrial Ecology Consultants.

# 3. Life Cycle Inventory Analysis

## 3.1. Data Collection Procedure

All primary data were collected using customized data collection templates, which were sent by email to the respective data providers in the participating facilities. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking. If gaps, outliers, or other inconsistencies occurred, Sphera engaged with the data provider to resolve any open issues.

## 3.2. Product System

### 3.2.1. Overview of Product System

AEC member companies produce surface-treated (anodized, painted), thermally improved, and/or mill finished aluminum extrusions.

The product life cycle modules are designated by ISO 21930, which specifically applies to the creation of building products and material EPDs. Modules A1-A3 represent the manufacturing, cradle-to-gate stage of the product. They can be further divided into the following modules:

A1 -- Raw material extraction and processing, processing of secondary material input

A2 -- Transport of materials to manufacturer

A3 -- Manufacturing

The use stage is excluded in this study, but the disposal is considered because of the significant recycling potential of the aluminum product. Modules C1 – C4 are required by the PCR. They are defined as:

C1 -- Deconstruction

C2 -- Transport to the disposal site

C3 -- Waste processing

C4 -- Disposal

However, C1 and C3 are to be reported as zero according to the PCR as they are assumed to fall below the cut-off criteria defined by ISO 21930. C2 is assumed as 100 km by truck. Materials for recycling (MR - 95%) for aluminum is reported in C1 module.

Module D is defined as benefits and loads beyond the product system boundary.

### 3.2.2. Production process

Figure 3-1 provides an overview of the manufacturing process for the aluminum extrusion products. The production stage starts with extraction and processing of aluminum ingot, billet, and ancillary materials, followed by the transportation of these materials to the plant. Billets, either cast on site or purchased from an external supplier, are extruded into profiles using steel dies. The extruded profiles may then be anodized or painted. Mill finished and surface-treated profiles may then undergo a thermal breaking process (thermal improvement). At EoL, the product is disassembled (e.g., during deconstruction of a building's façade) and materials are recovered for recycling. Raw material extraction and processing, processing of secondary material input, transport of materials to manufacturer, and manufacturing are included in the production, or cradle-to-gate, stage of the product. The use stage is excluded from system boundaries, but the disposal is considered because of the significant recycling potential of aluminum products.

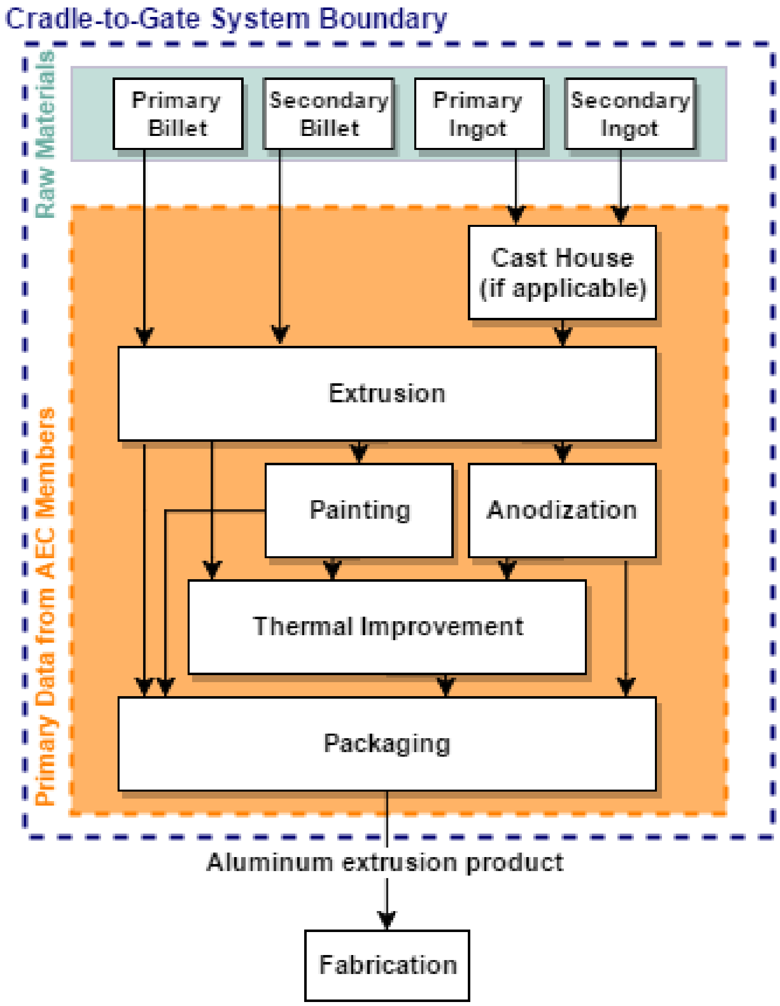


**Figure 3-1: Extrusion manufacturing diagram (Module A)**

## Extrusion

The production stage starts with extraction and processing of aluminum ingot, billet, and ancillary materials, followed by the transportation of these materials to the plant.

The extrusion manufacturing process, as shown in Figure -1 takes cast extrusion billet (round bar stock, produced from direct chill molds and typically ranging in diameter from 6 to 14 inches) and produces extruded profiles. The process begins with an inline preheat furnace that elevates the temperature of the billet to a predetermined level, around 900°F depending on the alloy. If not already cut to length, the billet is then sheared and placed into a hydraulic press, which then forces the semi-plastic billet through a heated steel die to form the desired shape. The length of the resulting extrusion is dictated by the take-off tables. The extrusions are air cooled or water quenched, with specific quench parameters dependent on alloy and desired microstructure and properties. The extrusion is then clamped and stretched to straighten the profile. Subsequently, the stretched profile is cut to length and then aged for several hours at elevated temperature (e.g. 350 °F) to achieve desired properties.

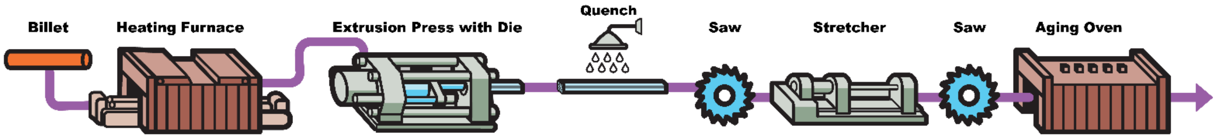


Figure 3-2: Extrusion manufacturing process schematic

### Painting

Extrusions to be painted are typically cleaned and then treated with a pre-coat in either a vertical or horizontal paint booth. Depending on the ultimate paint performance desired, a variety of pre-coats and primers may be employed. After pre-treatment, the extrusions will be coated with a liquid or powder paint and baked. Various paint formulations may be used depending on the desired performance.

### Anodization

If extrusions are to be anodized, they are cleaned and etched (with either caustic or acid etch) in a series of baths. Subsequently, they are immersed in an acid electrolyte bath and an electrical current is passed through the solution. A cathode is mounted to the inside of the anodizing tank, while the aluminum extrusions act as an anode. Oxygen ions are released from the electrolyte and combine with aluminum atoms at the surface of the extrusion being anodized, thereby creating a durable aluminum oxide layer fully integrated with the underlying aluminum. Organic or inorganic colorants can subsequently be added. The final step is a sealing stage to enhance durability.

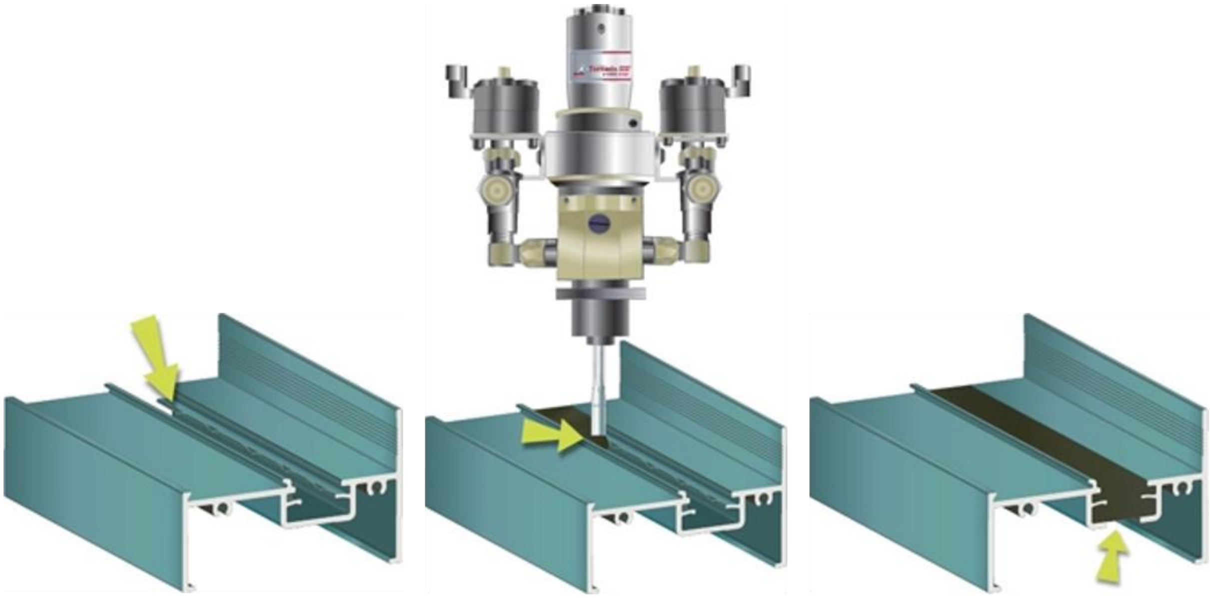
### Thermal improvement

Two alternative thermal barrier processes are typically used:

- A "pour & debridge" system in which a polyurethane liquid is allowed to harden in a "pocket" designed into the extrusion. The aluminum forming the pocket is then removed to allow the hardened polyurethane to act as an insulator.
- A polyamide strip system where a rigid polyamide strip is mechanically crimped between two extrusions designed to accept the strip—thus creating the insulator.

Basic pour & debridge and polyamide strip systems are shown below. Note that advanced approaches with multiple voids and/or insulating materials can be used for high levels of thermal performance.

Pour & Debridge: Creation of a thermal barrier using pour & debridge is a 3-step process:

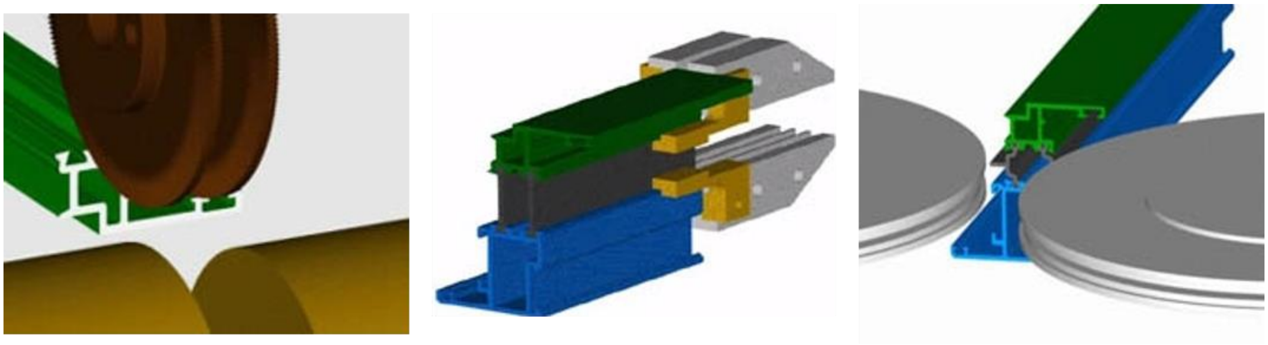


**1. Prepare**
The aluminum profile is extruded with a strategically placed channel to encapsulate an insulating polymer. The channel surface is conditioned with special equipment to create a "mechanical lock"

**2. Pour**
A two-part polymer is dispensed into the channel as a liquid, then hardens into a strong, structural insulating element

**3. Debridge**
The metal "bridge" is mechanically removed from the bottom of the channel, eliminating the conductive aluminum element and producing a non-metal-to-metal thermal barrier

Figure 3-3: Pour & debridge process



**1. Profile knurling**
A knurling wheel is used to produce "teeth" between 0.15 mm and 0.30 mm long in a pocket of the inner and outer extruded profiles that will be joined by the Strip to comprise the frame. These "teeth" will bite into the Strip during the crimping process and insure adequate shear strength for the composite profile.

**2. Strip insertion**
Typically, the Polyamide Strip is pulled or pushed into the extrusion profile, using specialized equipment. However, manual insertion can also be used, and there are assembly methods that pull or push the profile onto the Strip. The preferred method is up to the installer.

**3. Crimping**
Three sets of wheels rotate the extrusion onto the Strip and mechanically lock the components together. Over 1300 pounds of pressure is applied in stages, and the resulting aluminum/Strip assembly will then act as a load-bearing composite. Shear testing is typically conducted periodically to verify that the process has produced an assembly that will perform structurally as required.

Figure 3-4: Polyamide strip process

### 3.2.3. Product composition

Extruded aluminum products produced in North America typically contain a considerable proportion of metal recycled from aluminum scrap. The average metal composition of North American products, based on metal feedstock information collected from the companies participating in this EPD is shown in Table 3-1.

**Table 3-1: Metal composition of AEC extruded aluminum products**

| Category of Metal Source | Percentage (by mass) |
|---|---|
| Primary Metal (including alloying agents) | 47% |
| Recovered Aluminum Content | 53% |

The composition in the cast house aluminum ingots can be broken down into post-consumer and post-industrial scrap based on the available data and is shown in Table 3-2. Some cast house facilities had an input of secondary ingot, which had been categorized as post-consumer scrap for this calculation.

**Table 3-2: Metal Composition for cast house ingots**

| Category of Metal Source | Percentage (by mass) |
|---|---|
| Primary Metal (including alloying agents) | 30.3 % |
| Recovered Aluminum from Post-Industrial (Pre-Consumer) Scrap | 50.5 % |
| Recovered Aluminum from Post-Consumer Scrap | 19.2 % |

The definitions for post-industrial and post-consumer aluminum scrap are consistent with ISO 14021/25 and the related interpretations by UL Environment. Post-industrial scrap typically includes extrusion drop-offs from cutting, off-spec material, and scrap generated during subsequent processing by extruders or customers. Post-consumer scrap is scrap that has been used for an intended application as part of a previous product life cycle. It often includes aluminum wheels, wire, and reclaimed material from building demolition or renovation.

Extruded aluminum products produced for different customers, applications, and market sectors may vary substantially in metal composition, ranging from 100% primary aluminum to nearly 100% aluminum scrap. The alloy composition of a typical extrusion product as manufactured by AEC companies is described in Table 3-3.

**Table 3-3: 6063 aluminum alloy chemical composition (% by mass) as per Teal Sheet (AA, 2018)**

| | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Others (total) | Aluminum |
|---|---|---|---|---|---|---|---|---|---|---|
| Minimum | 0.20 | | -- | -- | 0.45 | | | | | remainder |
| Maximum | 0.60 | 0.35 | 0.10 | 0.10 | 0.90 | 0.10 | 0.10 | 0.10 | 0.15 | remainder |

Extrusions are made from both primary billet and secondary billet, with a varying degree of recycled metal content. Billets are either sourced externally or produced at a company-owned cast house. When produced at a company-owned cast house, internal process (run-around) scrap, post-industrial scrap, and post-consumer scrap are melted together with primary and secondary aluminum ingot feedstock sourced from an external supplier. Extruded aluminum products produced for different customers, applications, and market sectors may vary substantially in recycled content.

Definitions of the feedstocks used in the extrusion process are found in Table 3-4. The definitions of internal process (run-around) scrap, post-industrial scrap, and post-consumer scrap are consistent with the ISO 14021/25 (2006) standards and related interpretations by ULE (ULE, 2022).

**Table 3-4: Aluminum extrusion primary and secondary feedstocks**

| Aluminum Source | Definition |
|---|---|
| **Primary Ingot** | Prime aluminum that has not been processed in any way since its origination at a smelter |
| **Secondary Ingot** | A solid piece of cast scrap aluminum to be cast into billet |
| **Primary Billet** | Log or billet produced from hot molten aluminum directly from a smelter with negligible recycled content and that has not been solidified and re-melted prior to casting |
| **Secondary Billet** | A solid piece of cast scrap aluminum that originates from aluminum that is not in a molten state from a smelter |
| **Post-Consumer Scrap** | Scrap generated by the retirement of a consumer or industrial product e.g. wheels, wire, and reclaimed material from building demolition or renovation |
| **Post-Industrial Scrap (Pre-Consumer)** | Scrap generated by industrial or manufacturing waste that can be introduced into a melting process without substantial treatment e.g. extrusion drop-offs from cutting, off-spec material, and scrap generated during subsequent processing by extruders or fabricators |
| **Internal Process (Run-Around) scrap** | Scrap generated as part of a repeated closed-loop manufacturing process. Excluded from metal composition declaration. |

Data was only available for primary and secondary aluminum ingot. To ensure that the correct recycled content of purchased aluminum billet was modeled, the approach shown in Figure 3-5 was taken. All scrap was modeled as burden free when it enters the system since the model employs a “net scrap” approach (see section 2.4.2). When companies did not provide data for their own billet, primary ingot was modeled with the AA dataset, and the amount of secondary billet was calculated based on the ratio of primary ingot and aluminum scrap corresponding to the recycled content of the billet. Both primary ingot and aluminum scrap go through a remelting process. When companies were not able to provide the recycled content of their purchased secondary billet, an assumption of 75% recycled content was made based on the industry average.

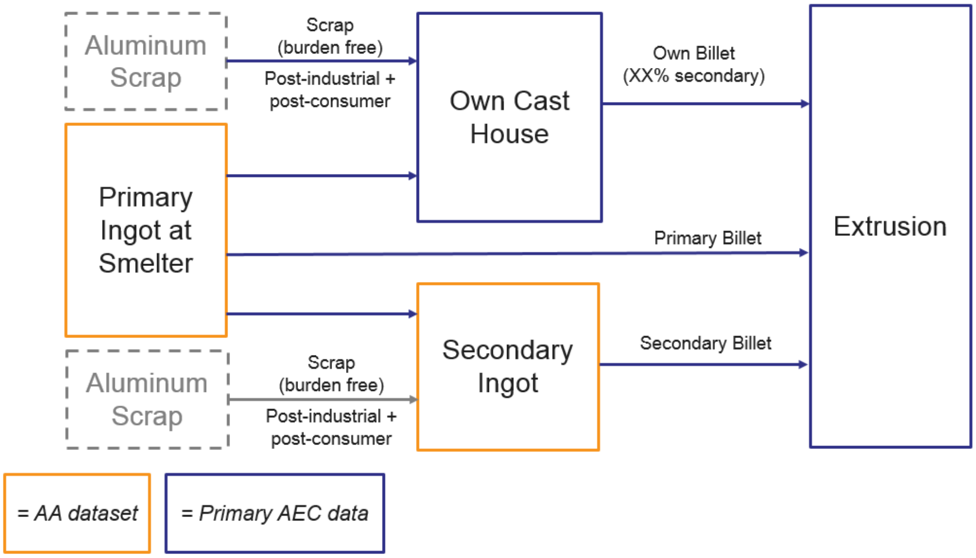


**Figure 3-5: Primary and secondary billet modeling approach**

As the extrusion process shapes the aluminum billet, only surface-treatment processes, i.e., anodizing and painting, alter the material content of the finished extrusion process. The percent by mass added by anodizing or painting is not large enough to significantly alter the percent by mass of the aluminum extrusion. The product composition of the extruded, anodized, painted, and thermally improved extrusions are shown in Table 3-5.

**Table 3-5: Material composition of the extrusion products under study*****

| | Extrusion, mill finish | Extrusion, painted | Extrusion, anodized** | Thermally improved extrusion, painted | Thermally improved extrusion, anodized** |
|---|---|---|---|---|---|
| Aluminum* | 100% | >95% | 100% | >92% | >96% |
| Paint | | <5% | | <5% | |
| *Acrylic* | - | *9%* | - | *9%* | - |
| *Polyester* | - | *68%* | - | *68%* | - |
| *PVDF* | - | *24%* | - | *24%* | - |
| Thermal break | | | | <4% | <4% |
| *Polyurethane* | - | - | - | *78%* | *78%* |
| *Polyamide* | - | - | - | *22%* | *22%* |

**As in Table 2-1, the aluminum extrusion itself prior to painting and/or thermal improvement should have a chemical composition of Al of 96.2% - 98.6%, depending on alloy.*

***Anodization chemicals do not adhere to the extrusion.*

****Percentages may not add up to 100%, as they are rounded to the nearest percent.*

It was also assumed that all secondary billet originated in North America. Secondary includes secondary billet, ingot, and post-consumer, post-industrial, and run-around scrap. On average, secondary billet contains 25% primary aluminum.

### 3.2.4. Production process

This section provides information on the inputs and outputs of the main unit processes. Unit process information for billet casting, extrusion, painting, anodizing and thermal improvement are found in Table 3-6 to Table 3-10 respectively.

Three of eight companies did not provide data for their own billet, so primary ingot was modeled using the Aluminum Association dataset, and secondary billet was modeled based on the ratio of primary ingot and aluminum scrap corresponding to the recycled content of the billet.

The weighted average is calculated across all company/plants. The 10th percentile is calculated ignoring zero values. Where some companies did not report data for some inputs, the weighted average reported is smaller than the 10th percentile for those cases.

**Table 3-6: Inputs and outputs for billet casting (cast house)**

| Type | Flow | Unit | Weighted average | 10th percentile | 90th percentile |
|---|---|---|---|---|---|
| **Inputs** | Primary aluminum ingot | kg | 3.06E+02 | 3.82E+02 | 2.39E+02 |
| | Secondary aluminum ingot | kg | 6.35E+00 | 4.30E+01 | 2.31E+01 |
| | Aluminum scrap (external, post-consumer scrap) | kg | 2.08E+02 | 3.90E+02 | 1.12E+02 |
| | Aluminum scrap (external, post-industrial scrap) | kg | 4.48E+02 | 6.25E+02 | 1.63E+02 |
| | Aluminum scrap (internal) | kg | 1.24E+02 | 5.76E+02 | 4.77E+01 |
| Secondary Alloying Elements | Magnesium | kg | 2.94E+00 | 3.96E+00 | 1.73E+00 |
| | Silicon | kg | 1.44E+00 | 2.34E+00 | 7.48E-01 |
| | Copper | kg | 1.44E+00 | 2.06E+00 | 3.43E-01 |
| | Manganese | kg | 3.54E-01 | 6.82E-01 | 1.69E-01 |
| | Ti Boron | kg | 1.16E+00 | 2.05E+00 | 6.41E-01 |
| | Chrome | kg | 1.78E-01 | 3.50E-01 | 7.88E-02 |
| | Vanadium | kg | 3.93E-02 | 1.30E+00 | 1.58E-01 |
| | Zirconium | kg | 1.81E-03 | 3.47E-02 | 3.47E-02 |
| | Titanium | kg | 6.57E-03 | 8.27E-02 | 8.27E-02 |
| | Iron | kg | 4.35E-02 | 1.25E-01 | 9.26E-02 |
| | Silica | kg | 1.88E-01 | 1.28E+00 | 1.07E+00 |
| | Salt Flux | kg | 1.92E-01 | 1.04E+00 | 8.58E-02 |

| | | | | | |
|---|---|---|---|---|---|
| Ancillary Materials | Bulk $O_2$ | kg | 1.01E-05 | 1.29E-04 | 1.29E-04 |
| | Bulk Argon | kg | 2.68E+00 | 2.60E+01 | 2.97E-02 |
| | Bulk Nitrogen | kg | 1.72E-01 | 6.46E+00 | 6.46E+00 |
| | Lubricants | kg | 9.27E-03 | 1.37E-01 | 3.46E-02 |
| | Solvent | kg | 2.04E-04 | 4.29E-03 | 4.29E-03 |
| | Boron nitride | kg | 1.42E-02 | 9.87E-02 | 6.70E-03 |
| | Bone ash | kg | 5.11E-02 | 1.36E-01 | 1.01E-01 |
| | Graphkote | kg | 2.19E-03 | 8.78E-03 | 8.78E-03 |
| | Sodium Chloride | kg | 1.92E-05 | 8.00E-04 | 8.00E-04 |
| | Filters | kg | 7.26E-02 | 2.17E-01 | 2.05E-01 |
| | Oils | kg | 3.22E-03 | 2.74E-02 | 6.51E-03 |
| Energy | Purchased electricity | MJ | 4.20E+02 | 1.21E+07 | 5.96E+04 |
| | Natural gas | MJ | 3.75E+02 | 1.55E+07 | 1.25E+03 |
| | Diesel (internal transport) | kg | 6.73E-01 | 1.04E+05 | 2.48E+04 |
| | Propane (internal transport) | kg | 8.44E-02 | 2.19E+04 | 1.39E+03 |
| Water | Municipal water | kg | 1.10E+03 | 2.03E+08 | 1.06E+03 |
| | Ground water (e.g. on-site well) | kg | 6.12E+01 | 1.44E+07 | 1.39E+07 |
| **Outputs** | Aluminum billet | kg | 1.00E+03 | -- | -- |
| Materials for Recovery | Aluminum to recycling (internal) | kg | 7.16E+01 | 1.57E+02 | 3.24E+01 |
| | Aluminum to recycling (external) | kg | 1.51E+01 | 2.26E+02 | 2.99E+01 |
| | Steel dies to recycling (external) | kg | 1.39E-01 | 2.93E+00 | 2.93E+00 |
| Wastes for Disposal | Waste water sent to municipal treatment | kg | 6.61E+02 | 2.82E+03 | 1.26E+02 |
| | Water treated on-site and discharged to river / lake | kg | 3.37E+02 | 0.00E+00 | 1.35E+03 |
| | Non-hazardous waste to landfill | kg | 5.42E+00 | 1.33E+01 | 1.47E+00 |
| | Non-hazardous waste to recovery | kg | 1.06E+01 | 2.57E+01 | 5.74E+00 |
| | Hazardous waste to recovery (dross) | kg | 2.27E+00 | 2.56E+01 | 2.45E+01 |
| Emissions to Air | Carbon dioxide | kg | 1.67E+02 | 3.14E+02 | 2.47E+02 |
| | Carbon monoxide | kg | 3.01E-01 | 4.29E-01 | 1.15E-01 |
| | Dust (PM2.5) | kg | 2.26E-02 | 4.53E-02 | 1.94E-02 |
| | Dust (PM10) | kg | 4.80E-01 | 1.91E-01 | 2.85E-02 |
| | Dust (total) | kg | 5.26E-02 | 1.28E-01 | 4.19E-02 |

| | | | | | |
|---|---|---|---|---|---|
| | Methane | kg | 1.50E-03 | 4.77E-03 | 4.46E-03 |
| | Nitrogen oxides | kg | 3.31E-01 | 3.21E-01 | 7.36E-03 |
| | Nitrous oxide ($N_2O$) | kg | 2.61E-02 | 6.68E-03 | 4.57E-04 |
| | NMVOC | kg | 1.41E-02 | 7.00E-02 | 4.58E-03 |
| | Sulfur oxides | kg | 4.44E-03 | 1.78E-02 | 7.50E-04 |
| | HCl | kg | 2.83E-04 | 2.34E+02 | 2.34E+02 |
| | F | kg | 5.58E-02 | 4.63E+04 | 4.63E+04 |

### Table 3-7: Inputs and outputs for extrusion process

| Type | Flow | Unit | Weighted average | 10th percentile | 90th percentile |
|---|---|---|---|---|---|
| **Inputs** | Primary aluminum billet (purchased) | kg | 4.27E+02 | 1.21E+03 | 1.55E+01 |
| | Secondary aluminum billet (purchased) | kg | 2.29E+02 | 9.13E+02 | 1.55E+01 |
| | Post-consumer scrap | kg | 7.38E-01 | 5.83E+02 | 1.06E+02 |
| | Post-industrial scrap | kg | 6.64E+00 | 5.25E+03 | 9.57E+02 |
| | Aluminum billet (from own cast house) | kg | 7.68E+02 | 1.64E+03 | 8.46E+02 |
| | Hydraulic oil | kg | 9.85E+00 | 1.12E+05 | 9.25E+00 |
| | Dies | kg | 4.28E+00 | 1.86E+01 | 8.38E-01 |
| Ancillary Materials | Sodium hydroxide (Caustic) | kg | 2.65E+00 | 1.94E+01 | 1.25E-02 |
| | Sodium hydroxide | kg | 1.77E+01 | 4.47E+01 | 2.84E+00 |
| | Lubricant | kg | 5.38E-02 | 5.81E-01 | 1.33E-01 |
| | Trough filters | kg | 2.56E-03 | 5.14E-02 | 5.14E-02 |
| | Boron Nitride | kg | 3.13E-04 | 7.19E-03 | 7.19E-03 |
| | Potassium hydroxide | kg | 2.24E-03 | 7.48E-02 | 7.48E-02 |
| | Chrome phosphate | kg | 2.12E-02 | 7.10E-01 | 7.10E-01 |
| | Fluoride accelerator | kg | 1.31E-02 | 4.38E-01 | 4.38E-01 |
| | Aluminum chloride | kg | 3.27E-03 | 1.09E-01 | 1.09E-01 |
| | Sodium Bisufite 50% | kg | 1.13E-02 | 3.79E-01 | 3.79E-01 |
| | Bulk Nitrogen | kg | 1.68E+00 | 1.76E+01 | 2.96E+00 |
| | Die cleaner, cleaning agent (solvent) | kg | 1.54E-01 | 9.70E-01 | 9.70E-01 |
| | Ammonia Anhydrous | kg | 1.31E-02 | 1.75E-01 | 3.46E-02 |
| | Pallets | kg | 1.65E-04 | 2.33E+01 | 4.19E-02 |
| | Wood | kg | 4.28E-04 | 4.66E+01 | 9.80E-01 |

| | | | | | |
|---|---|---|---|---|---|
| | Steel strapping | kg | 2.54E-06 | 9.94E-01 | 3.49E-02 |
| | Plastic strapping | kg | 1.70E-05 | 1.51E+00 | 1.02E-01 |
| | Paper | kg | 4.05E-05 | 1.64E+00 | 9.46E-02 |
| | Cardboard | kg | 1.90E-03 | 3.39E+01 | 1.49E-01 |
| | Plastic film | kg | 1.26E-05 | 1.02E+00 | 6.98E-02 |
| | Fabric | kg | 1.18E-06 | 4.37E-01 | 3.84E-02 |
| | Foam | kg | 3.02E-06 | 6.30E-01 | 2.54E-03 |
| | Tape | kg | 2.13E-06 | 1.50E+00 | 1.78E-01 |
| | Fiberglass strapping | kg | 3.33E-07 | 2.63E-01 | 2.63E-01 |
| Energy | Purchased electricity | MJ | 7.02E+03 | 2.28E+07 | 1.61E+06 |
| | Natural gas | MJ | 8.14E-04 | 1.34E+08 | 1.03E+06 |
| | Gasoline (internal transport) | kg | 9.63E-03 | 2.84E+03 | 5.05E+02 |
| | Diesel (internal transport) | kg | 5.46E-01 | 9.55E+04 | 3.57E+03 |
| | Propane (internal transport) | kg | 1.04E+00 | 8.83E+04 | 2.23E+03 |
| Water | Municipal water | kg | 5.69E+03 | 8.37E+07 | 2.95E+06 |
| | Ground water (e.g. on-site well) | kg | 6.63E+01 | 3.52E+07 | 1.72E+07 |
| **Outputs** | Total Aluminum extrusion | kg | 1.00E+03 | -- | -- |
| Materials for Recovery | Aluminum to recycling (internal) | kg | 3.00E+02 | 5.96E+02 | 1.90E+02 |
| | Aluminum to recycling (external) | kg | 1.11E+02 | 4.95E+02 | 1.89E+01 |
| | Steel dies to recycling (external) | kg | 2.06E+00 | 6.79E+00 | 7.87E-01 |
| Wastes for Disposal | Waste water sent to municipal treatment | kg | 5.59E+03 | 2.23E+03 | 3.46E+02 |
| | Water treated on-site and discharged to river / lake | kg | 3.19E+01 | 2.29E+03 | 2.29E+03 |
| | Non-hazardous waste to landfill | kg | 1.07E+01 | 5.08E+01 | 6.17E-01 |
| | Non-hazardous waste to recovery | kg | 1.13E+01 | 5.75E+01 | 3.72E+00 |
| | Non-hazardous waste to incineration | kg | 3.22E-02 | 1.38E+00 | 1.38E+00 |
| | Hydraulic oil to disposal | kg | 4.85E+00 | 5.22E+00 | 4.26E-01 |
| | Spent caustic - solids / sludge - neutralized off-site | kg | 3.15E+00 | 6.66E+01 | 7.01E+00 |
| Emissions to Air | Carbon dioxide | kg | 1.25E+02 | 4.49E+02 | 6.14E+01 |
| | Carbon monoxide | kg | 9.96E+00 | 7.30E+01 | 2.49E-02 |
| | Dust (PM2.5) | kg | 3.00E-02 | 2.65E-01 | 2.52E-03 |
| | Dust (PM10) | kg | 5.80E-02 | 4.79E-01 | 5.02E-03 |
| | Methane | kg | 1.04E-03 | 6.31E-03 | 1.29E-03 |
| | Nitrogen oxides | kg | 2.30E-01 | 5.31E-01 | 3.14E-02 |

| | | | | | |
|---|---|---|---|---|---|
| | Nitrous oxide ($N_2O$) | kg | 1.25E-01 | 7.01E-01 | 2.30E-04 |
| | NMVOC | kg | 1.04E-01 | 6.56E-01 | 3.85E-03 |
| | Sulfur oxides | kg | 1.40E-02 | 1.32E-02 | 3.99E-04 |
| | Other HAPs | kg | 2.99E-05 | 1.57E-03 | 1.57E-03 |
| | Ammonia | kg | 3.86E-03 | 3.01E-02 | 1.20E-02 |
| Emissions to Water | Ammonia | kg | 3.18E-03 | 3.09E-02 | 1.14E-02 |

**Table 3-8: Inputs and outputs for painting process**

| Type | Flow | Unit | Weighted average | 10th percentile | 90th percentile |
|---|---|---|---|---|---|
| **Inputs** | Aluminum extrusion input | kg | 1.03E+03 | 1.09E+03 | 1.00E+03 |
| Paint/Coatings/ Powder | PVDF (powder) | kg | 1.44E-01 | 8.32E+00 | 8.32E+00 |
| | Polyester (powder) | kg | 7.57E+00 | 3.92E+01 | 3.92E+01 |
| Paint/Coatings/ Liquid | PVDF | kg | 1.10E+01 | 4.64E+01 | 1.36E+01 |
| | Polyester | kg | 2.42E+01 | 9.27E+01 | 4.12E-01 |
| | Acrylic | kg | 4.14E+00 | 3.46E+01 | 1.54E+00 |
| | Solvents | kg | 6.52E+00 | 2.28E+01 | 6.29E-01 |
| Pre-treatment and WW Chemicals | Chrome pre-treatment chemicals | kg | 4.48E+01 | 3.43E+01 | 4.86E-01 |
| | Non-chrome pre-treatment chemicals | kg | 8.50E+00 | 3.42E+01 | 1.94E+00 |
| | HOUGHTO-COAT A-830, A-840, A-860 | kg | 6.58E-02 | 3.81E+00 | 3.81E+00 |
| | Wt-water conditioner | kg | 8.03E-01 | 2.50E+01 | 2.50E+01 |
| | Sulfuric Acid 93% | kg | 1.10E-02 | 3.43E-01 | 3.43E-01 |
| | AZOTE (Nitrogen) | kg | 2.54E-03 | 7.93E-02 | 7.93E-02 |
| | HCFC/HFC Refrigerant | kg | 3.97E-05 | 2.05E-04 | 2.05E-04 |
| | Lubricant | kg | 5.89E-03 | 5.07E-02 | 3.90E-02 |
| | Alcohol (Ethanol, Isopropyl alcohol) | kg | 6.53E-03 | 6.80E-02 | 6.80E-02 |
| | Xylene | kg | 1.19E-01 | 1.24E+00 | 1.24E+00 |
| | Glycol ether | kg | 4.80E-01 | 5.00E+00 | 5.00E+00 |
| Energy and Utilities | Water | kg | 1.75E+03 | 3.16E+03 | 3.28E+02 |
| | Purchased electricity | MJ | 3.41E+02 | 3.32E+03 | 7.22E+02 |
| | Natural gas | MJ | 1.53E+05 | 7.91E+03 | 2.38E+03 |
| | Propane | kg | 1.28E+00 | 2.58E+01 | 1.28E+00 |

| | | | | | |
|---|---|---|---|---|---|
| | Gasoline | kg | 6.86E-03 | 7.14E-02 | 7.14E-02 |
| **Outputs** | Painted aluminum extrusions | kg | 1.00E+03 | -- | -- |
| | Scrap (internal) | kg | 1.79E+01 | 8.13E+01 | 1.33E+01 |
| | Scrap (external) | kg | 2.12E+01 | 8.16E+01 | 3.05E+01 |
| Wastes for Disposal | Non-hazardous waste to landfill | kg | 2.09E+00 | 1.18E+01 | 4.55E-01 |
| | Non-hazardous waste to recovery | kg | 6.35E+01 | 3.85E+02 | 8.88E+00 |
| | Hydraulic oil to disposal | kg | 8.27E-02 | 2.22E+00 | 2.80E-01 |
| | Wastewater sent to municipal treatment | kg | 1.69E+03 | 3.16E+03 | 3.43E+02 |
| | Non-hazardous waste to incineration | kg | 9.97E-01 | 9.42E+00 | 4.14E+00 |
| | NMVOC | kg | 2.91E-01 | 2.05E+00 | 8.92E-03 |
| | Zinc | kg | 1.48E-05 | 2.25E-04 | 2.25E-04 |
| | Chromium | kg | 1.44E-06 | 2.20E-05 | 2.20E-05 |
| | Carbon dioxide | kg | 8.37E+01 | 4.35E+02 | 5.05E+01 |
| | Carbon monoxide | kg | 4.69E-02 | 2.54E-01 | 1.34E-02 |
| | Dust (PM10) | kg | 1.61E-02 | 8.72E-02 | 5.66E-03 |
| | Methane | kg | 1.60E-03 | 8.30E-03 | 9.74E-04 |
| | Nitrogen oxides (NOx) | kg | 8.19E-02 | 3.63E-01 | 6.01E-04 |
| | Sulfur oxides (SOx) | kg | 4.50E-04 | 2.26E-03 | 2.27E-04 |

### Table 3-9: Inputs and outputs for anodization process

| Type | Flow | Unit | Weighted average | 10th percentile | 90th percentile |
|---|---|---|---|---|---|
| **Inputs** | Cleaning agent | kg | 1.74E+00 | 5.85E+00 | 1.37E+00 |
| | De-oxidizing agent | kg | 6.62E+01 | 1.09E+02 | 3.05E+01 |
| | Paint | kg | 3.08E+00 | 7.61E+00 | 3.11E-01 |
| | Etch additive | kg | 3.70E+00 | 3.59E+01 | 2.51E+00 |
| | Seal additive | kg | 2.96E+00 | 6.92E+00 | 1.45E+00 |
| | Caustic agent | kg | 4.30E+01 | 1.26E+02 | 6.79E-01 |
| | Etch acid | kg | 7.10E+00 | 2.23E+01 | 1.37E+01 |
| | Ammonium hydroxide (NH4OH) | kg | 1.07E-01 | 8.05E-01 | 8.05E-01 |
| | Defoamer | kg | 7.95E-02 | 4.46E-01 | 1.46E-01 |
| | Nitric acid (HNO3) | kg | 4.96E+00 | 3.15E+01 | 3.51E+00 |
| | Non-ionic surfactant | kg | 3.39E+00 | 2.73E+01 | 6.21E-01 |
| | Rinse smut deterrent | kg | 9.23E-02 | 9.71E-01 | 9.71E-01 |

| | | | | | |
|---|---|---|---|---|---|
| | Seal smut deterrent | kg | 1.63E-02 | 1.71E-01 | 1.71E-01 |
| | Lubricant/oil | kg | 2.72E-02 | 3.84E-01 | 3.84E-01 |
| | Coagulant | kg | 1.97E-04 | 1.69E-03 | 1.69E-03 |
| | H2O2, de-ox additive | kg | 1.27E+00 | 8.64E+00 | 1.47E+00 |
| | Magnesium hydroxide | kg | 2.95E-01 | 4.83E+00 | 4.83E+00 |
| | NH4F | kg | 2.21E-01 | 3.62E+00 | 3.62E+00 |
| | 2532 HI SEAL ADDITIVE | kg | 3.47E-01 | 2.45E+00 | 2.45E+00 |
| | 2513 SEAL, Sodium sulfite | kg | 7.92E-01 | 5.60E+00 | 5.60E+00 |
| | HCl | kg | 3.89E-02 | 2.75E-01 | 2.75E-01 |
| | H3PO4 | kg | 2.69E+00 | 1.90E+01 | 1.90E+01 |
| Ancillary Materials | Steel for clamps and header hardware | kg | 7.76E-02 | 8.38E-01 | 8.38E-01 |
| | Weld wire | kg | 5.78E-03 | 6.24E-02 | 6.24E-02 |
| | Lubricant/oil | kg | 1.13E-03 | 1.22E-02 | 1.22E-02 |
| Energy | Purchased electricity | MJ | 7.27E+03 | 1.04E+04 | 1.60E+03 |
| | Natural gas | MJ | 5.22E+03 | 1.77E+04 | 1.39E+02 |
| | Gasoline | kg | 2.26E-02 | 2.15E-01 | 2.91E-02 |
| | Diesel | kg | 3.45E-02 | 4.88E-01 | 4.88E-01 |
| | Propane | kg | 8.32E-01 | 2.74E+00 | 8.53E-01 |
| Water | Municipal water | kg | 9.71E+03 | 3.03E+04 | 2.74E+03 |
| **Outputs** | Anodized aluminum extrusion | kg | 1.00E+03 | -- | -- |
| Wastes | Aluminum to recycling (internal) | kg | 1.31E-02 | 5.00E+01 | 1.28E+01 |
| | Aluminum to recycling (external) | kg | 4.92E-03 | 4.58E+01 | 2.63E+01 |
| | Waste water sent to municipal treatment | kg | 6.78E+03 | 2.77E+04 | 2.11E+03 |
| | Water treated on-site and discharged to river / lake | kg | 4.38E+02 | 4.73E+03 | 4.73E+03 |
| | Non-hazardous waste to landfill | kg | 7.12E+01 | 4.12E+02 | 1.17E+01 |
| | Non-hazardous waste to recovery | kg | 3.03E+01 | 1.92E+02 | 4.24E+01 |
| | Dross sent to recovery | kg | 2.00E+01 | 2.11E+02 | 2.11E+02 |
| | Hazardous waste to disposal | kg | 5.57E+00 | 9.13E+01 | 9.13E+01 |
| Emissions | Carbon dioxide | kg | 7.83E+01 | 3.06E+02 | 4.65E+01 |
| | Carbon monoxide | kg | 2.68E-01 | 1.64E+00 | 2.98E-01 |
| | Dust (PM2.5) | kg | 7.00E-02 | 3.59E-01 | 1.90E-02 |
| | Dust (PM10) | kg | 2.48E-02 | 2.24E-01 | 2.97E-02 |
| | Dust (total) | kg | 9.36E-02 | 5.33E-01 | 1.90E-02 |
| | Methane | kg | 1.45E-03 | 6.36E-03 | 6.36E-03 |

| | | | | | |
|---|---|---|---|---|---|
| | Nitrogen oxides | kg | 9.03E-02 | 3.12E-01 | 1.12E-01 |
| | Nitrous oxide ($N_2O$) | kg | 1.47E-04 | 6.49E-04 | 6.49E-04 |
| | NMVOC | kg | 6.15E-03 | 2.64E-02 | 1.67E-02 |
| | Sulfur oxides | kg | 1.29E-03 | 6.39E-03 | 2.15E-03 |
| | Ammonia | kg | 7.04E-03 | 2.20E-02 | 2.20E-02 |
| | Nitrogen | kg | 1.73E-02 | 1.87E-01 | 1.87E-01 |
| | Aluminum | kg | 3.96E-03 | 1.74E-02 | 1.74E-02 |
| | Lead | kg | 2.88E-05 | 2.03E-04 | 2.03E-04 |
| | Copper | kg | 1.68E-03 | 1.19E-02 | 1.19E-02 |

**Table 3-10: Inputs and outputs for thermal improvement process**

| Type | | Unit | Weighted average | 10th percentile | 90th percentile |
|---|---|---|---|---|---|
| **Inputs** | Painted aluminum extrusion | kg | 4.94E+02 | 9.21E+02 | 3.54E+02 |
| | Anodized aluminum extrusion | kg | 5.04E+02 | 7.64E+02 | 1.23E+02 |
| | Polyurethane | kg | 3.09E+01 | 6.16E+01 | 4.37E+01 |
| | Polyamide | kg | 8.75E+00 | 1.28E+02 | 7.78E+00 |
| Ancillary Materials | Isocyanic Acid, Polymethylenepolyphenylene | kg | 1.68E+01 | 4.44E+01 | 4.05E+01 |
| | Thermal Barrier Polymer Part "B" | kg | 1.79E+01 | 4.48E+01 | 4.40E+01 |
| | Compressor oil | kg | 5.81E-03 | 3.32E-02 | 3.32E-02 |
| Energy | Purchased electricity | MJ | 3.72E+03 | 1.95E+05 | 3.54E+02 |
| | Natural gas | MJ | 6.31E+03 | 1.43E+05 | 5.69E+04 |
| | Gasoline (internal transport) | kg | 1.09E-01 | 6.19E-01 | 6.19E-01 |
| | Propane (internal transport) | kg | 2.16E+00 | 1.39E+01 | 1.83E+00 |
| Water | Municipal water | kg | 1.08E+04 | 8.85E+04 | 2.80E+04 |
| **Outputs** | Aluminum extrusion to consumer | Kg | 1.00E+03 | -- | -- |
| | Aluminum to recycling (internal) | kg | 1.61E+01 | 5.97E+01 | 9.64E+00 |
| | Aluminum to recycling (external) | kg | 2.86E+01 | 8.15E+01 | 1.38E+01 |
| | Wastewater sent to municipal treatment | kg | 1.08E+04 | 8.85E+04 | 2.80E+04 |
| | NMVOC | kg | 3.35E-02 | 1.91E-01 | 1.91E-01 |

### 3.2.5. End-of-life

At the life cycle level, aluminum was modeled as part of a closed-loop recycling approach. A 95% recycling rate was used for the aluminum extrusion and a credit was assigned to the life cycle equal to the substituted burden of primary production, accounting for the burden from scrap collection, processing, re-melting and casting. This net credit was reported in module D. The 95% recycling rate is a global estimate for aluminum in the building and transportation sectors (EAA, 2021) (AA, 2022) which has been supported by minimum values published in a United Nations report (UNEP, 2011). The remaining 5% not captured in the recycling loop are landfilled and are reported in module C4.

## 3.3. Background Data

Documentation for all GaBi datasets can be found at http://www.gabi-software.com/america/support/gabi/.

### 3.3.1. Fuels and energy

National/regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2021.2 databases. Table 3-11 shows the most relevant LCI datasets used in modeling the product systems. Electricity consumption was modeled using national/regional grid mixes that account for imports from neighboring countries/regions.

**Table 3-11: Key energy datasets used in inventory analysis**

| Material / Process | Geo. Ref. | Dataset name | Data Provider | Ref. Year | Proxy?* |
|---|---|---|---|---|---|
| **Diesel** | US | Diesel mix at filling station | Sphera | 2021 | No |
| **Electricity** | US | Electricity grid mix – AKGD | Sphera | 2021 | No |
| | US | Electricity grid mix – AKMS | Sphera | 2021 | No |
| | US | Electricity grid mix – AZNM | Sphera | 2021 | No |
| | US | Electricity grid mix – CAMX | Sphera | 2021 | No |
| | US | Electricity grid mix – ERCT | Sphera | 2021 | No |
| | US | Electricity grid mix – FRCC | Sphera | 2021 | No |
| | US | Electricity grid mix – HIMS | Sphera | 2021 | No |
| | US | Electricity grid mix – HIOA | Sphera | 2021 | No |
| | US | Electricity grid mix – MROE | Sphera | 2021 | No |
| | US | Electricity grid mix – MROW (without MISO) | Sphera | 2020 | No |
| | US | Electricity grid mix – NEWE | Sphera | 2021 | No |
| | US | Electricity grid mix – NWPP | Sphera | 2021 | No |
| | US | Electricity grid mix – NYCW | Sphera | 2021 | No |
| | US | Electricity grid mix – NYLI | Sphera | 2021 | No |
| | US | Electricity grid mix – NYUP | Sphera | 2021 | No |
| | US | Electricity grid mix – RFCE | Sphera | 2021 | No |
| | US | Electricity grid mix – RFCM | Sphera | 2021 | No |
| | US | Electricity grid mix – RFCW | Sphera | 2021 | No |
| | US | Electricity grid mix – RMPA | Sphera | 2021 | No |
| | US | Electricity grid mix – SPNO | Sphera | 2021 | No |

| | | | | | |
|---|---|---|---|---|---|
| | US | Electricity grid mix – SPSO | Sphera | 2021 | No |
| | US | Electricity grid mix – SRMV | Sphera | 2021 | No |
| | US | Electricity grid mix – SRMW | Sphera | 2021 | No |
| | US | Electricity grid mix – SRSO | Sphera | 2021 | No |
| | US | Electricity grid mix – SRTV | Sphera | 2021 | No |
| | US | Electricity grid mix – SRVC | Sphera | 2021 | No |
| | US | Electricity grid mix (eGRID) | Sphera | 2021 | No |
| **Fuel Oil** | US | Thermal energy from heavy fuel oil (HFO) | Sphera | 2021 | No |
| | US | Thermal energy from light fuel oil (LFO) | Sphera | 2021 | No |
| **Gasoline** | US | Gasoline mix (premium, 100% fossil) at filling station | Sphera | 2021 | No |
| **Natural gas** | US | Thermal energy from natural gas | Sphera | 2021 | No |
| **Propane** | US | Propane at refinery | Sphera | 2021 | No |
| | US | Thermal energy from propane | Sphera | 2021 | No |

### 3.3.2. Raw materials and processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2021.2 database. Table 3-12 shows the most relevant LCI datasets used in modeling the product systems.

**Table 3-12: Key material and process datasets used in inventory analysis**

| Material / Process | Dataset name | Geo. Ref. | Data Provider | Ref. Year | Proxy* |
|---|---|---|---|---|---|
| **Primary Aluminum** | Primary aluminum ingot | RNA | AA | 2021 | No |
| **Secondary Aluminum** | Secondary aluminum ingot (95% recycled content) | RNA | AA | 2021 | No |
| **Water** | Tap water from surface water | US | Sphera | 2021 | No |
| **Alloying elements** | | | | | |
| *Mg* | Magnesium | CN | Sphera | 2021 | No |
| *Si* | Silicon mix (99%) | GLO | Sphera | 2021 | No |
| *Cu* | Copper (99.99%; cathode) | GLO | ICA | 2021 | No |
| *Mn* | Manganese | GLO | Sphera | 2021 | No |
| *Titanium alloy* | Titanium alloy (Ti6Al4V) | GLO | Sphera | 2021 | No |
| *MgCl2* | Magnesium chloride | DE | Sphera | 2021 | Geo |
| *Ferro chrome* | Ferro chrome high carbon, consumption mix | DE | Sphera | 2021 | Geo |
| *Ferro-Vanadium* | Ferro-Vanadium | ZA | Sphera | 2021 | Geo |
| *Zirconium silicate* | Zirconium silicate | GLO | Sphera | 2021 | No |
| *Titanium* | Titanium | GLO | Sphera | 2021 | No |

| | | | | | |
|---|---|---|---|---|---|
| *Iron ore mix* | Iron ore mix | US | Sphera | 2021 | No |
| *Ar* | Argon (highly pure) | US | Sphera | 2021 | No |
| *Oxygen* | Oxygen (gaseous) | US | Sphera | 2021 | No |
| *N2* | Nitrogen (gaseous) | US | Sphera | 2021 | No |
| *NH3* | Ammonia (high purity) | DE | Sphera | 2021 | No |
| *Boron trioxide* | Boron trioxide (estimation) | DE | Sphera | 2021 | No |
| *NaHCO3* | Sodium bicarbonate | US | Sphera | 2021 | No |
| *NaCl* | Sodium chloride (rock salt) | US | Sphera | 2021 | No |
| *Si sand* | Silica sand (flour) | US | Sphera | 2021 | No |
| **Extrusion chemicals** | | | | | |
| *Sodium hydroxide* | Sodium hydroxide (caustic soda) mix (100%) | EU-28 | Sphera | 2021 | Geo |
| *Trough filter* | Glass fibre mesh | DE | Sphera | 2021 | Geo |
| *Paint* | Water based paint white (EN15804 A1-A3) | DE | Sphera | 2021 | No |
| *Potassium hydroxide* | Potassium hydroxide (KOH) | US | Sphera | 2021 | Geo |
| *Chrome phosphate* | Dispersion agent (mixture of phosphate with polyacrylate) | GLO | Sphera | 2021 | Tech |
| *Sodium sulfite* | Sodium hydrogen sulfite (from NaOH and SO2) | US | Sphera | 2021 | No |
| *Aluminium chloride* | Aluminium chloride (approximation) | IN | Sphera | 2021 | Geo |
| *Flouride accelerator* | Aluminium fluoride | DE | Sphera | 2021 | Geo |
| *Steel die* | Fabricated steel plate - American Inst. of Steel Construction (AISC) (A1-A3) | US | Sphera | 2021 | No |
| *Solvent* | Rinsing-agent (100% solvents) | DE | Sphera | 2021 | Geo |
| **Paint and chemicals** | | | | | |
| *Primer* | Clear coat powder | DE | Sphera | 2021 | Geo |
| *Paint (solid)* | Coating powder (industry; outside; black) | DE | Sphera | 2021 | Geo |
| *Paint (PVDF)* | Polyvinylidene fluoride (PVDF) | DE | Sphera | 2021 | Geo |
| *Paint (liquid)* | Emulsion paint (synthetic resin) | EU-28 | Sphera | 2021 | Geo |
| *Paint solvent* | Solvents (for can manufacturing) | US | Sphera | 2021 | No |
| *Cleaning agent* | Non-ionic surfactant (ethylene oxid dervatives) | GLO | Sphera | 2021 | No |
| *Pre-treatment chemicals* | Coagulant mix | DE | Sphera | 2021 | Geo |
| | Application base coat/primer water-based (windows, white) | DE | Sphera | 2021 | Geo |
| | Ferrous sulfate | US | Sphera | 2021 | No |
| | Sulphuric acid aq. (96%) | US | Sphera | 2021 | No |
| | Nitrogen (liquid) | US | Sphera | 2021 | No |
| | Refrigerant 407 C | DE | Sphera | 2021 | No |
| | Benzyl alcohol | EU-28 | Sphera | 2021 | Geo |

| | | | | | |
|---|---|---|---|---|---|
| | o-Xylene | US | Sphera | 2021 | No |
| | Ethylene glycol | US | Sphera | 2021 | No |
| **Anodizing chemicals** | | | | | |
| *Sulphuric acid and de-ox agent* | Sulphuric acid (75%) | US | Sphera | 2021 | No |
| *EDTA* | Ethylenediaminetetraacetic acid (EDTA) (estimated) | US | Sphera | 2021 | No |
| *Ammonium biflouride* | Hydrogen fluoride | DE | Sphera | 2021 | No |
| $NH_4OH$ | Ammonia water (weight share 25% $NH_3$) | US | Sphera | 2021 | No |
| *Defoamer* | Defoamer | DE | Sphera | 2021 | Geo |
| *Nitric acid* | Nitric acid (60%) | US | Sphera | 2021 | No |
| *Hydrazine* | Hydrazine hydrate/hydrazine (estimation) | US | Sphera | 2021 | No |
| *Nickel acetate* | Vinyl acetate (Acetic acid vinyl ester, VAM) | US | Sphera | 2021 | No |
| *Alkylbenzenesulfonate* | Sodium alkylbenzenesulfonate (from benzene and paraffins over alkyl chloride) | DE | Sphera | 2021 | No |
| *HCl* | Hydrochloric acid 32% (primarily from chlorine, H2 Cracker) | US | Sphera | 2021 | No |
| $H_2O_2$ | Hydrogen peroxide aq. (highly pure, 30%) | US | Sphera | 2021 | No |
| *Naphthalene* | Naphthalene [estimated] | EU-28 | Sphera | 2021 | No |
| $Mg(OH)_2$ | Magnesium Hydroxide (from sea water) | EU-28 | Sphera | 2021 | No |
| $H_3PO_4$ | Phosphoric acid (highly pure) | US | Sphera | 2021 | No |
| *Seal (Sealing agent)* | Sodium acetate (2011) | US | Sphera | 2021 | No |
| **Thermal Improvement** | | | | | |
| *PU foam* | Polyurethane foam (PUR) | DE | Sphera | 2021 | No |
| *PA 6* | Polyamide 6 Granulate (PA 6) Mix | DE | Sphera | 2021 | No |
| *Melamin resin* | Melamin resin (MF) | US | Sphera | 2021 | No |
| *Polyester Resin* | Polyester Resin (unsaturated) (UP) | US | Sphera | 2021 | No |
| *Aliphatic Isocyanates* | Aliphatic Isocyanates | EU-28 | ALIPA | 2021 | Geo |
| *Thermoplastic polymer* | Thermoplastic starch polymer (TPS), unblended | US | Sphera | 2021 | No |
| *Coating solvent* | Coating solvent-based (industry; white) (approximation) | US | Sphera | 2021 | No |
| **Waste treatment** | | | | | |
| *Waste water* | Municipal waste water treatment (mix) | US | Sphera | 2020 | No |
| | Glass/inert on landfill Sphera | US | Sphera | 2020 | No |
| **Packaging** | | | | | |
| | Softwood lumber | RNA | CORRIM | 2021 | No |
| | Softwood plywood | RNA | CORRIM | 2021 | No |
| | Steel wire rod | GLO | Worldsteel | 2021 | No |

| | | | | | |
|---|---|---|---|---|---|
| | Nylon (PA 6.6) - yarn | RNA | Sphera | 2021 | No |
| | Kraft paper (EN15804 A1-A3) | RNA | Sphera | 2021 | No |
| | Average Corrugated Product | US | CPA | 2021 | No |
| | Polyethylene film (LDPE/PE-LD) | US | Sphera | 2021 | No |
| | Cotton - fabric (based on US cotton yarn, conventional) | US | Sphera | 2021 | No |
| | Elastomer joint tape, silicone rubber (EN15804 A1-A3) | DE | Sphera | 2021 | Geo |
| | Glass fibres | US | Sphera | 2021 | No |

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

### 3.3.3. Transportation

Average transportation distances and modes of transport are included for the transport of major raw materials to production and assembly facilities.

The GaBi 2021 database was used to model transportation. Truck transportation within the United States was modeled using the GaBi U.S. truck transportation datasets based on fuel economy data from the U.S. EPA's SmartWay program and emissions data from the U.S. EPA's MOVES model.

**Table 3-13: Transportation datasets used in the inventory**

| Transport/Fuel | Geographic Reference | Dataset name | Data Provider | Ref. Year | Proxy?* |
|---|---|---|---|---|---|
| **Mode** | | | | | |
| Ship | GLO | Bulk commodity carrier, average, ocean going | Sphera | 2021 | No |
| Rail | GLO | Rail transport cargo - average, average train, gross tonne weight 1,000t / 726t payload capacity | Sphera | 2021 | No |
| Truck | US | Truck - heavy/bulk (EPA SmartWay) | Sphera | 2021 | No |
| **Fuel** | | | | | |
| Diesel | US | Diesel mix at filling station | Sphera | 2017 | No |
| Fuel oil | US | Heavy fuel oil at refinery (2.5w.% S) | Sphera | 2017 | No |

* No = no proxy used; Tech. = technological proxy; Geo. = geographic proxy

# 4. LCIA Results

This section contains the results for the impact categories and additional metrics defined in section 0. 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

The life cycle impact results for the various extrusion products are presented in Table 4-1 through Table 4-5. The majority of impacts lie with the production stage of the life cycle. Module D burdens are negative due to the credit given for recycling at EoL. While all extrusion products have the same recycling rate and recycled content, the generation of scrap during the finishing processes leads to an increased credit in module D compared to the mill finished extrusion.

### 4.1.1. Mill finish extrusion

**Table 4-1: Life cycle impact assessment results per metric ton of aluminum extrusion products (Mill Finish)**

| Impact Category | Unit | A1 | A2 | A3 | C1 | C2 | C4 | D |
|---|---|---|---|---|---|---|---|---|
| Life Cycle Impacts Assessment (LCIA) Results | | | | | | | | |
| *IPCC, AR5 (IPCC, 2013)* | | | | | | | | |
| Global warming potential (GWP 100) | kg $CO_2$ eq. | 7.80E+03 | 1.27E+01 | 2.44E+03 | - | 1.02E+01 | 2.20E+00 | -8.38E+03 |
| *TRACI v2.1* | | | | | | | | |
| Ozone depletion potential (ODP) | kg CFC 11 eq. | 1.86E-10 | 2.55E-15 | 2.82E-07 | - | 2.13E-15 | 7.35E-15 | -2.81E-12 |
| Acidification potential (AP) | kg $SO_2$ eq. | 3.43E+01 | 7.67E-02 | 3.07E+00 | - | 1.97E-02 | 9.37E-03 | -3.93E+01 |
| Eutrophication potential (EP) | kg N eq. | 7.93E-01 | 5.95E-03 | 2.29E-01 | - | 2.83E-03 | 5.22E-04 | -8.70E-01 |
| Smog formation potential (SFP) | kg $O_3$ eq. | 2.94E+02 | 1.96E+00 | 6.08E+01 | - | 4.46E-01 | 1.66E-01 | -3.22E+02 |
| *CML-IA v4.8* | | | | | | | | |
| Abiotic resource depletion potential of non-renewable (fossil) energy resources ($ADP_{fossil}$) | MJ | 7.44E+04 | 1.82E+02 | 3.10E+04 | - | 1.50E+02 | 3.29E+01 | -7.54E+04 |
| Resource Use Indicators | | | | | | | | |

|  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
| Renewable primary resources used as energy carrier (fuel) (RPR$_E$) | MJ | 4.64E+04 | 7.17E+00 | 3.96E+03 | - | 6.23E+00 | 2.80E+00 | -5.45E+04 |
| Renewable primary resources with energy content used as material (RPR$_M$) | MJ | - | - | 3.32E-05 | - | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Non-renewable primary resources used as an energy carrier (fuel) (NRPR$_E$) | MJ | 7.60E+04 | 1.83E+02 | 3.65E+04 | - | 1.51E+02 | 3.36E+01 | -7.67E+04 |
| Non-renewable primary resources with energy content used as material (NRPR$_M$) | MJ | - | - | 6.60E+02 | - | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Renewable secondary fuels (RSF) | MJ | - | - | - | - | - | - | - |
| Non-renewable secondary fuels (NRSF) | MJ | - | - | - | - | - | - | - |
| Recovered energy (RE) | MJ | - | - | - | - | - | - | - |
| Secondary materials (SM) | kg | 9.48E+02 | - | - | - | - | - | - |
| Use of net fresh water resources (FW) | m$^3$ | 1.54E+02 | 3.05E-02 | 1.78E+01 | - | 2.66E-02 | 4.62E-03 | -1.80E+02 |
| OUTPUT FLOWS & WASTE FLOWS |  |  |  |  |  |  |  |  |
| Hazardous waste disposed (HWD) | kg | 4.83E-05 | 1.45E-08 | 3.74E-06 | - | 1.26E-08 | 3.18E-09 | -4.66E-05 |
| Non-hazardous waste disposed (NHWD) | kg | 2.80E+03 | 1.69E-02 | 3.20E+01 | - | 1.39E-02 | 1.00E+02 | -3.30E+03 |
| High-level radioactive waste, conditioned, to final repository (HLRW) | kg | 7.48E-04 | 5.93E-07 | 2.86E-03 | - | 5.09E-07 | 3.24E-07 | -6.56E-04 |
| Intermediate- and low-level radioactive waste, conditioned, to final repository (ILLRW) | kg | 1.93E-02 | 1.63E-05 | 7.89E-02 | - | 1.40E-05 | 8.63E-06 | -1.66E-02 |
| Components for re-use (CRU) | kg | - | - | - | - | - | - | - |
| Materials for recycling (MFR) | kg | - | - | 3.86E+02 | 1.04E+03 | - | - | 2.65E+00 |
| Materials for energy recovery (MER) | kg | - | - | - | - | - | - | - |
| Recovered energy exported from the product system (EE) | MJ | - | - | - | - | - | - | - |

### 4.1.2. Anodized extrusion

**Table 4-2 : Life cycle impact assessment results per metric ton of aluminum extrusion products (Anodized)**

| Impact Category | Unit | A1 | A2 | A3 | C1 | C2 | C4 | D |
|---|---|---|---|---|---|---|---|---|
| LIFE CYCLE IMPACTS ASSESSMENT (LCIA) RESULTS | | | | | | | | |
| *IPCC, AR5 (IPCC, 2013)* | | | | | | | | |
| Global warming potential (GWP 100) | kg $CO_2$ eq. | 7.88E+03 | 1.28E+01 | 2.87E+03 | - | 1.02E+01 | 2.20E+00 | -8.48E+03 |
| *TRACI v2.1* | | | | | | | | |
| Ozone depletion potential (ODP) | kg CFC 11 eq. | 1.88E-10 | 2.58E-15 | 6.78E-07 | - | 2.13E-15 | 7.35E-15 | -2.84E-12 |
| Acidification potential (AP) | kg $SO_2$ eq. | 3.47E+01 | 7.75E-02 | 4.17E+00 | - | 1.97E-02 | 9.37E-03 | -3.97E+01 |
| Eutrophication potential (EP) | kg N eq. | 8.02E-01 | 6.02E-03 | 3.11E-01 | - | 2.83E-03 | 5.22E-04 | -8.81E-01 |
| Smog formation potential (SFP) | kg $O_3$ eq. | 2.98E+02 | 1.98E+00 | 7.37E+01 | - | 4.46E-01 | 1.66E-01 | -3.26E+02 |
| *CML-IA v4.8* | | | | | | | | |
| Abiotic resource depletion potential of non-renewable (fossil) energy resources ($ADP_{fossil}$) | MJ | 7.52E+04 | 1.84E+02 | 3.66E+04 | - | 1.50E+02 | 3.29E+01 | -7.63E+04 |
| RESOURCE USE INDICATORS | | | | | | | | |
| Renewable primary resources used as energy carrier (fuel) ($RPR_E$) | MJ | 4.69E+04 | 7.25E+00 | 5.33E+03 | - | 6.23E+00 | 2.80E+00 | -5.51E+04 |
| Renewable primary resources with energy content used as material ($RPR_M$) | MJ | - | - | 3.36E-05 | - | - | - | - |
| Non-renewable primary resources used as an energy carrier (fuel) ($NRPR_E$) | MJ | 7.68E+04 | 1.85E+02 | 4.39E+04 | - | 1.51E+02 | 3.36E+01 | -7.77E+04 |
| Non-renewable primary resources with energy content used as material ($NRPR_M$) | MJ | - | - | 6.69E+02 | - | - | - | - |
| Renewable secondary fuels (RSF) | MJ | - | - | - | - | - | - | - |
| Non-renewable secondary fuels (NRSF) | MJ | - | - | - | - | - | - | - |
| Recovered energy (RE) | MJ | - | - | - | - | - | - | - |
| Secondary materials (SM) | kg | 9.58E+02 | - | - | - | - | - | - |
| Use of net fresh water resources (FW) | $m^3$ | 1.56E+02 | 3.09E-02 | 3.16E+01 | - | 2.66E-02 | 4.62E-03 | -1.83E+02 |
| OUTPUT FLOWS & WASTE FLOWS | | | | | | | | |
| Hazardous waste disposed (HWD) | kg | 4.88E-05 | 1.47E-08 | 5.58E+00 | - | 1.26E-08 | 3.18E-09 | -4.72E-05 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Non-hazardous waste disposed (NHWD) | kg | 2.83E+03 | 1.71E-02 | 7.34E+01 | - | 1.39E-02 | 1.00E+02 | -3.34E+03 |
| High-level radioactive waste, conditioned, to final repository (HLRW) | kg | 7.57E-04 | 5.99E-07 | 3.73E-03 | - | 5.09E-07 | 3.24E-07 | -6.64E-04 |
| Intermediate- and low-level radioactive waste, conditioned, to final repository (ILLRW) | kg | 1.95E-02 | 1.65E-05 | 1.03E-01 | - | 1.40E-05 | 8.63E-06 | -1.68E-02 |
| Components for re-use (CRU) | kg | - | - | - | - | - | - | - |
| Materials for recycling (MFR) | kg | - | - | 3.90E+02 | 1.06E+03 | - | - | 2.68E+00 |
| Materials for energy recovery (MER) | kg | - | - | - | - | - | - | - |
| Recovered energy exported from the product system (EE) | MJ | - | - | - | - | - | - | - |

### 4.1.3. Painted extrusion

**Table 4-3 : Life cycle impact assessment results per metric ton of aluminum extrusion products (Painted)**

| Impact Category | Unit | A1 | A2 | A3 | C1 | C2 | C4 | D |
|---|---|---|---|---|---|---|---|---|
| LIFE CYCLE IMPACTS ASSESSMENT (LCIA) RESULTS | | | | | | | | |
| *IPCC, AR5 (IPCC, 2013)* | | | | | | | | |
| Global warming potential (GWP 100) | kg $CO_2$ eq. | 8.18E+03 | 1.30E+01 | 3.48E+03 | - | 1.02E+01 | 2.20E+00 | -8.54E+03 |
| *TRACI v2.1* | | | | | | | | |
| Ozone depletion potential (ODP) | kg CFC 11 eq. | 1.29E-06 | 2.62E-15 | 9.96E-06 | - | 2.13E-15 | 7.35E-15 | -2.86E-12 |
| Acidification potential (AP) | kg $SO_2$ eq. | 3.55E+01 | 7.86E-02 | 4.45E+00 | - | 1.97E-02 | 9.37E-03 | -4.00E+01 |
| Eutrophication potential (EP) | kg N eq. | 8.43E-01 | 6.10E-03 | 3.60E-01 | - | 2.83E-03 | 5.22E-04 | -8.87E-01 |
| Smog formation potential (SFP) | kg $O_3$ eq. | 3.08E+02 | 2.01E+00 | 8.59E+01 | - | 4.46E-01 | 1.66E-01 | -3.29E+02 |
| *CML-IA v4.8* | | | | | | | | |
| Abiotic resource depletion potential of non-renewable (fossil) energy resources ($ADP_{fossil}$) | MJ | 8.04E+04 | 1.86E+02 | 4.64E+04 | - | 1.50E+02 | 3.29E+01 | -7.68E+04 |
| RESOURCE USE INDICATORS | | | | | | | | |
| Renewable primary resources used as energy carrier (fuel) ($RPR_E$) | MJ | 4.80E+04 | 7.35E+00 | 5.59E+03 | - | 6.23E+00 | 2.80E+00 | -5.55E+04 |
| Renewable primary resources with energy content used as material ($RPR_M$) | MJ | - | - | 3.41E-05 | -- | - | - | - |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Non-renewable primary resources used as an energy carrier (fuel) (NRPR$_E$) | MJ | 8.22E+04 | 1.88E+02 | 5.12E+04 | - | 1.51E+02 | 3.36E+01 | -7.82E+04 |
| Non-renewable primary resources with energy content used as material (NRPR$_M$) | MJ | - | - | 2.60E+03 | - | - | - | - |
| Renewable secondary fuels (RSF) | MJ | - | - | - | - | - | - | - |
| Non-renewable secondary fuels (NRSF) | MJ | - | - | - | - | - | - | - |
| Recovered energy (RE) | MJ | - | - | - | - | - | - | - |
| Secondary materials (SM) | kg | 9.72E+02 | - | - | - | - | - | - |
| Use of net fresh water resources (FW) | m$^3$ | 1.59E+02 | 3.13E-02 | 2.34E+01 | - | 2.66E-02 | 4.62E-03 | -1.84E+02 |
| OUTPUT FLOWS & WASTE FLOWS | | | | | | | | |
| Hazardous waste disposed (HWD) | kg | 5.01E-05 | 1.49E-08 | 4.88E-02 | - | 1.26E-08 | 3.18E-09 | -4.75E-05 |
| Non-hazardous waste disposed (NHWD) | kg | 2.88E+03 | 1.73E-02 | 3.80E+01 | - | 1.39E-02 | 1.00E+02 | -3.36E+03 |
| High-level radioactive waste, conditioned, to final repository (HLRW) | kg | 8.37E-04 | 6.08E-07 | 3.43E-03 | - | 5.09E-07 | 3.24E-07 | -6.69E-04 |
| Intermediate- and low-level radioactive waste, conditioned, to final repository (ILLRW) | kg | 2.16E-02 | 1.67E-05 | 9.45E-02 | - | 1.40E-05 | 8.63E-06 | -1.69E-02 |
| Components for re-use (CRU) | kg | - | - | - | - | - | - | - |
| Materials for recycling (MFR) | kg | - | - | 3.96E+02 | 1.06E+03 | - | - | 2.72E+00 |
| Materials for energy recovery (MER) | kg | - | - | - | - | - | - | - |
| Recovered energy exported from the product system (EE) | MJ | - | - | - | - | - | - | - |

### 4.1.4. Thermally treated anodized extrusion

**Table 4-4 : Life cycle impact assessment results per metric ton of thermally treated anodized aluminum extrusion products**

| Impact Category | Unit | A1 | A2 | A3 | C1 | C2 | C4 | D |
|---|---|---|---|---|---|---|---|---|
| LIFE CYCLE IMPACTS ASSESSMENT (LCIA) RESULTS | | | | | | | | |
| *IPCC, AR5 (IPCC, 2013)* | | | | | | | | |
| Global warming potential (GWP 100) | kg CO$_2$ eq. | 8.28E+03 | 2.65E+01 | 3.49E+03 | - | 1.02E+01 | 2.20E+00 | -8.61E+03 |
| *TRACI v2.1* | | | | | | | | |
| Ozone depletion potential (ODP) | kg CFC 11 eq. | 3.76E-07 | 5.42E-15 | 6.77E-07 | - | 2.13E-15 | 7.35E-15 | -2.88E-12 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Acidification potential (AP) | kg $SO_2$ eq. | 3.53E+01 | 1.18E-01 | 4.66E+00 | - | 1.97E-02 | 9.37E-03 | -4.03E+01 |
| Eutrophication potential (EP) | kg N eq. | 1.03E+00 | 1.07E-02 | 3.53E-01 | - | 2.83E-03 | 5.22E-04 | -8.94E-01 |
| Smog formation potential (SFP) | kg $O_3$ eq. | 3.09E+02 | 2.91E+00 | 8.44E+01 | - | 4.46E-01 | 1.66E-01 | -3.31E+02 |
| ***CML-IA v4.8*** | | | | | | | | |
| Abiotic resource depletion potential of non-renewable (fossil) energy resources ($ADP_{fossil}$) | MJ | 8.27E+04 | 3.83E+02 | 4.65E+04 | - | 1.50E+02 | 3.29E+01 | -7.74E+04 |
| | | | | RESOURCE USE INDICATORS | | | | |
| Renewable primary resources used as energy carrier (fuel) ($RPR_E$) | MJ | 4.79E+04 | 1.55E+01 | 6.01E+03 | - | 6.23E+00 | 2.80E+00 | -5.60E+04 |
| Renewable primary resources with energy content used as material ($RPR_M$) | MJ | - | - | 3.36E-05 | - | - | - | - |
| Non-renewable primary resources used as an energy carrier (fuel) ($NRPR_E$) | MJ | 8.10E+04 | 3.86E+02 | 5.44E+04 | - | 1.51E+02 | 3.36E+01 | -7.88E+04 |
| Non-renewable primary resources with energy content used as material ($NRPR_M$) | MJ | 3.57E+03 | - | 6.68E+02 | - | - | - | - |
| Renewable secondary fuels (RSF) | MJ | - | - | - | - | - | - | - |
| Non-renewable secondary fuels (NRSF) | MJ | - | - | - | - | - | - | - |
| Recovered energy (RE) | MJ | - | - | - | - | - | - | - |
| Secondary materials (SM) | kg | 9.57E+02 | - | - | - | - | - | - |
| Use of net fresh water resources (FW) | $m^3$ | 1.59E+02 | 6.63E-02 | 4.41E+01 | - | 2.66E-02 | 4.62E-03 | -1.85E+02 |
| | | | | OUTPUT FLOWS & WASTE FLOWS | | | | |
| Hazardous waste disposed (HWD) | kg | 4.96E-05 | 3.15E-08 | 5.57E+00 | - | 1.26E-08 | 3.18E-09 | -4.79E-05 |
| Non-hazardous waste disposed (NHWD) | kg | 2.84E+03 | 3.56E-02 | 7.64E+01 | - | 1.39E-02 | 1.00E+02 | -3.39E+03 |
| High-level radioactive waste, conditioned, to final repository (HLRW) | kg | 8.98E-04 | 1.28E-06 | 3.97E-03 | - | 5.09E-07 | 3.24E-07 | -6.74E-04 |
| Intermediate- and low-level radioactive waste, conditioned, to final repository (ILLRW) | kg | 2.32E-02 | 3.52E-05 | 1.10E-01 | - | 1.40E-05 | 8.63E-06 | -1.71E-02 |
| Components for re-use (CRU) | kg | - | - | - | - | - | - | - |
| Materials for recycling (MFR) | kg | - | - | 3.90E+02 | 1.07E+03 | - | - | 2.67E+00 |
| Materials for energy recovery (MER) | kg | - | - | - | - | - | - | - |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Recovered energy exported from the product system (EE) | MJ | - | - | - | - | - | - | - |

### 4.1.5. Thermally treated painted extrusion

**Table 4-5 : Life cycle impact assessment results per metric ton of thermally treated painted aluminum extrusion products**

| Impact Category | Unit | A1 | A2 | A3 | C1 | C2 | C4 | D |
|---|---|---|---|---|---|---|---|---|
| LIFE CYCLE IMPACTS ASSESSMENT (LCIA) RESULTS | | | | | | | | |
| *IPCC, AR5 (IPCC, 2013)* | | | | | | | | |
| Global warming potential (GWP 100) | kg $CO_2$ eq. | 8.57E+03 | 2.66E+01 | 4.10E+03 | - | 1.02E+01 | 2.20E+00 | -8.67E+03 |
| *TRACI v2.1* | | | | | | | | |
| Ozone depletion potential (ODP) | kg CFC 11 eq. | 1.66E-06 | 5.46E-15 | 9.95E-06 | - | 2.13E-15 | 7.35E-15 | -2.90E-12 |
| Acidification potential (AP) | kg $SO_2$ eq. | 3.61E+01 | 1.19E-01 | 4.94E+00 | - | 1.97E-02 | 9.37E-03 | -4.06E+01 |
| Eutrophication potential (EP) | kg N eq. | 1.07E+00 | 1.08E-02 | 4.02E-01 | - | 2.83E-03 | 5.22E-04 | -9.00E-01 |
| Smog formation potential (SFP) | kg $O_3$ eq. | 3.18E+02 | 2.94E+00 | 9.65E+01 | - | 4.46E-01 | 1.66E-01 | -3.34E+02 |
| *CML-IA v4.8* | | | | | | | | |
| Abiotic resource depletion potential of non-renewable (fossil) energy resources ($ADP_{fossil}$) | MJ | 8.79E+04 | 3.86E+02 | 5.64E+04 | - | 1.50E+02 | 3.29E+01 | -7.80E+04 |
| RESOURCE USE INDICATORS | | | | | | | | |
| Renewable primary resources used as energy carrier (fuel) ($RPR_E$) | MJ | 4.89E+04 | 1.56E+01 | 6.26E+03 | - | 6.23E+00 | 2.80E+00 | -5.63E+04 |
| Renewable primary resources with energy content used as material ($RPR_M$) | MJ | - | - | 3.40E-05 | - | - | - | - |
| Non-renewable primary resources used as an energy carrier (fuel) ($NRPR_E$) | MJ | 8.64E+04 | 3.89E+02 | 6.16E+04 | - | 1.51E+02 | 3.36E+01 | -7.94E+04 |
| Non-renewable primary resources with energy content used as material ($NRPR_M$) | MJ | 3.57E+03 | - | 2.60E+03 | - | - | - | - |
| Renewable secondary fuels (RSF) | MJ | - | - | - | - | - | - | - |
| Non-renewable secondary fuels (NRSF) | MJ | - | - | - | - | - | - | - |
| Recovered energy (RE) | MJ | - | - | - | - | - | - | - |
| Secondary materials (SM) | kg | 9.71E+02 | - | - | - | - | - | - |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Use of net fresh water resources (FW) | m³ | 1.62E+02 | 6.67E-02 | 3.59E+01 | - | 2.66E-02 | 4.62E-03 | -1.87E+02 |
| OUTPUT FLOWS & WASTE FLOWS | | | | | | | | |
| Hazardous waste disposed (HWD) | kg | 5.09E-05 | 3.17E-08 | 4.88E-02 | - | 1.26E-08 | 3.18E-09 | -4.82E-05 |
| Non-hazardous waste disposed (NHWD) | kg | 2.88E+03 | 3.58E-02 | 4.10E+01 | - | 1.39E-02 | 1.00E+02 | -3.41E+03 |
| High-level radioactive waste, conditioned, to final repository (HLRW) | kg | 9.78E-04 | 1.29E-06 | 3.67E-03 | - | 5.09E-07 | 3.24E-07 | -6.79E-04 |
| Intermediate- and low-level radioactive waste, conditioned, to final repository (ILLRW) | kg | 2.53E-02 | 3.54E-05 | 1.01E-01 | - | 1.40E-05 | 8.63E-06 | -1.72E-02 |
| Components for re-use (CRU) | kg | - | - | - | - | - | - | - |
| Materials for recycling (MFR) | kg | - | - | 3.95E+02 | 1.08E+03 | - | - | 2.71E+00 |
| Materials for energy recovery (MER) | kg | - | - | - | - | - | - | - |
| Recovered energy exported from the product system (EE) | MJ | - | - | - | - | - | - | - |

## 4.2. Contribution Analysis By Life Cycle Stages

Figure 4-1

Figure 4-1presents the detailed contribution results of the extrusion process. The primary drivers of burden are the inputs of aluminum: primary and secondary billet purchases as well as billet coming from companies' own cast houses, which is made from a mix of primary and secondary ingot. Module A1 represents more than 75% of GWP and is the most significant driver of impacts in the extrusion process across all categories. Figures 4-2 through 4-5 show the same contribution results for the other finishes, and the results are in general not substantially different from the mill finish results shown in Figure 4-1.

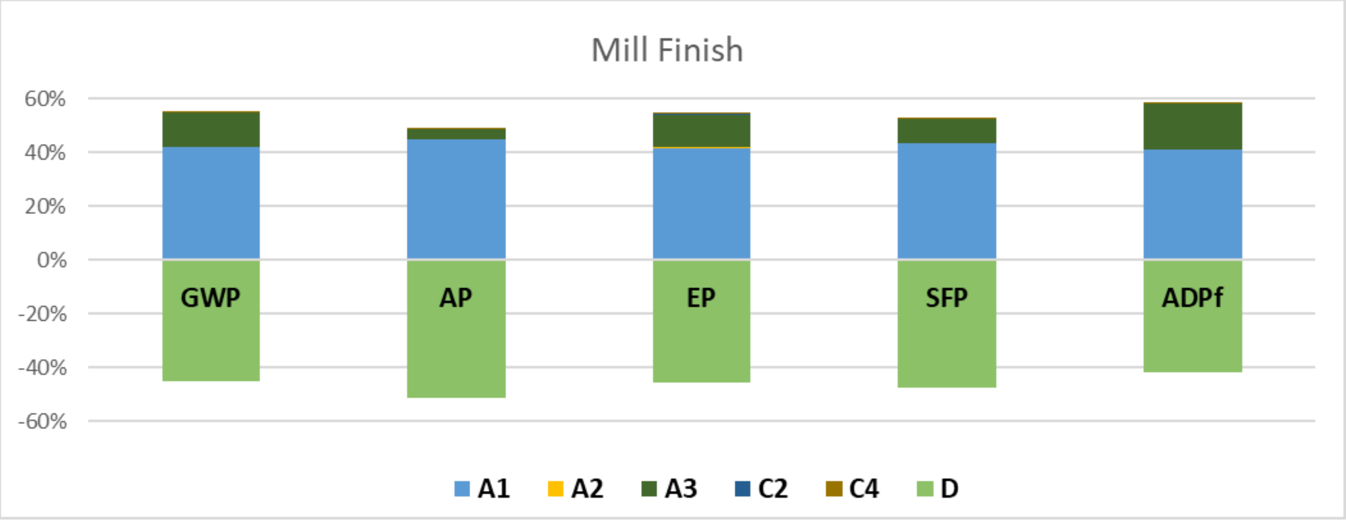


Figure 4-1: Mill finish extrusion relative environmental impacts of all life cycle stages

Figure 4-2 presents the relative results of the anodized extrusion. Similar to the mill finish product, environmental burdens are driven by the recovery or extraction of feedstock materials, furnace and melt shop operations, and casting. The benefits on the environmental burden resulting from reuse, energy recovery and recycling of aluminum scrap are also relevant, as are the manufacturing and final processing stages.

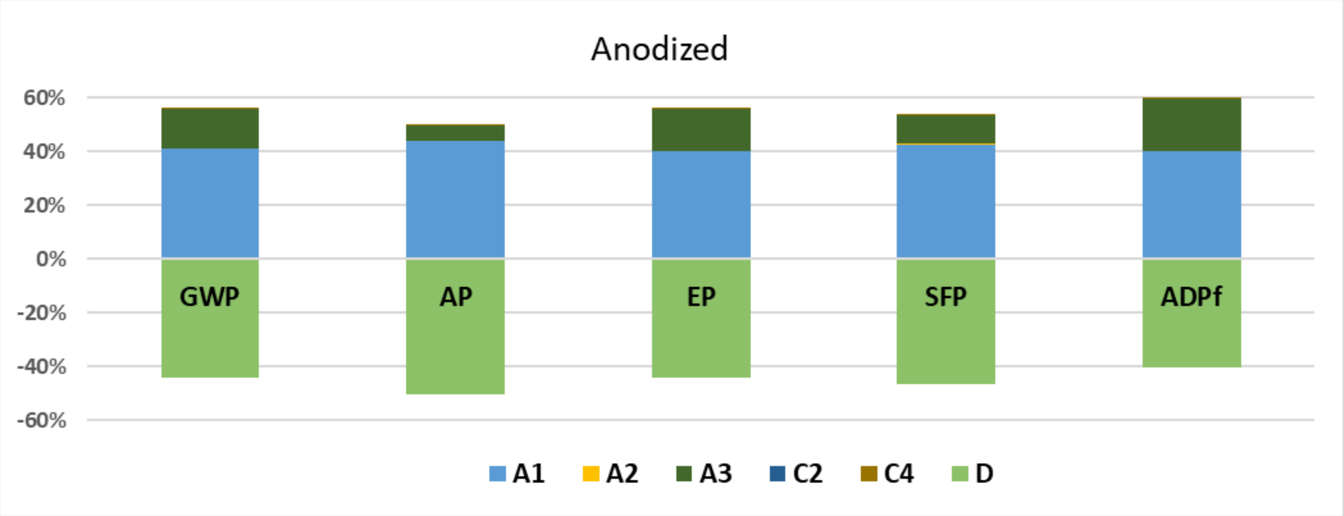


Figure 4-2: Anodized extrusion relative environmental impacts of all life cycle stages

Figure 4-3 represents painted extrusion results.

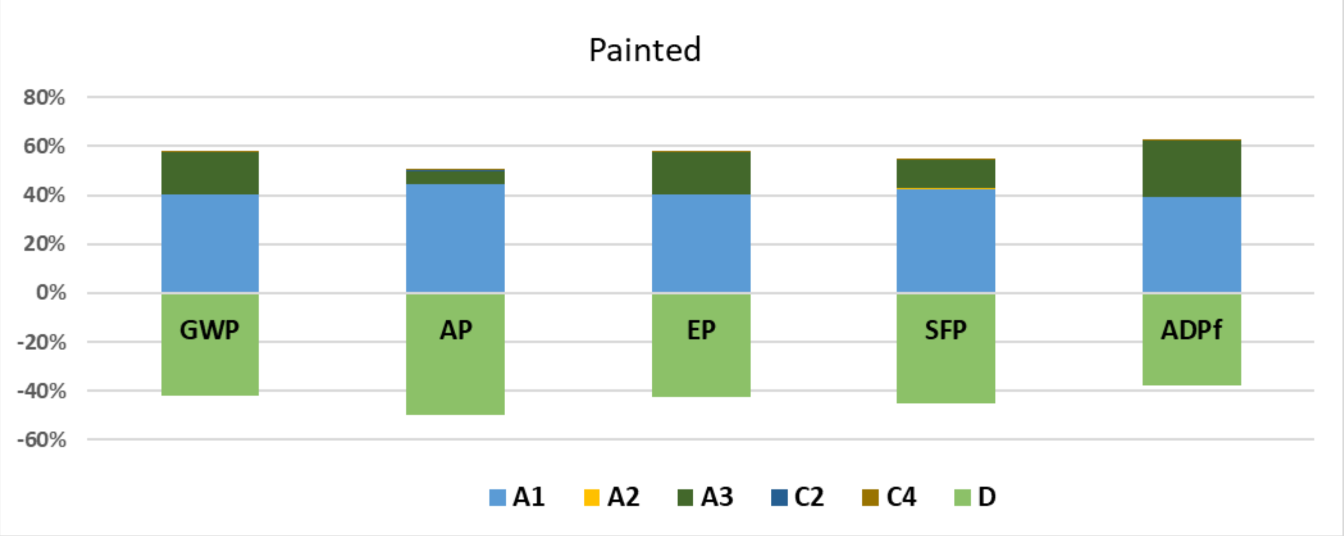


Figure 4-3: Painted extrusion relative environmental impacts of all life cycle stages

Figure 4-4, Figure 4-5, and Figure 4-6 present the thermally improved painted, and anodized relative results.

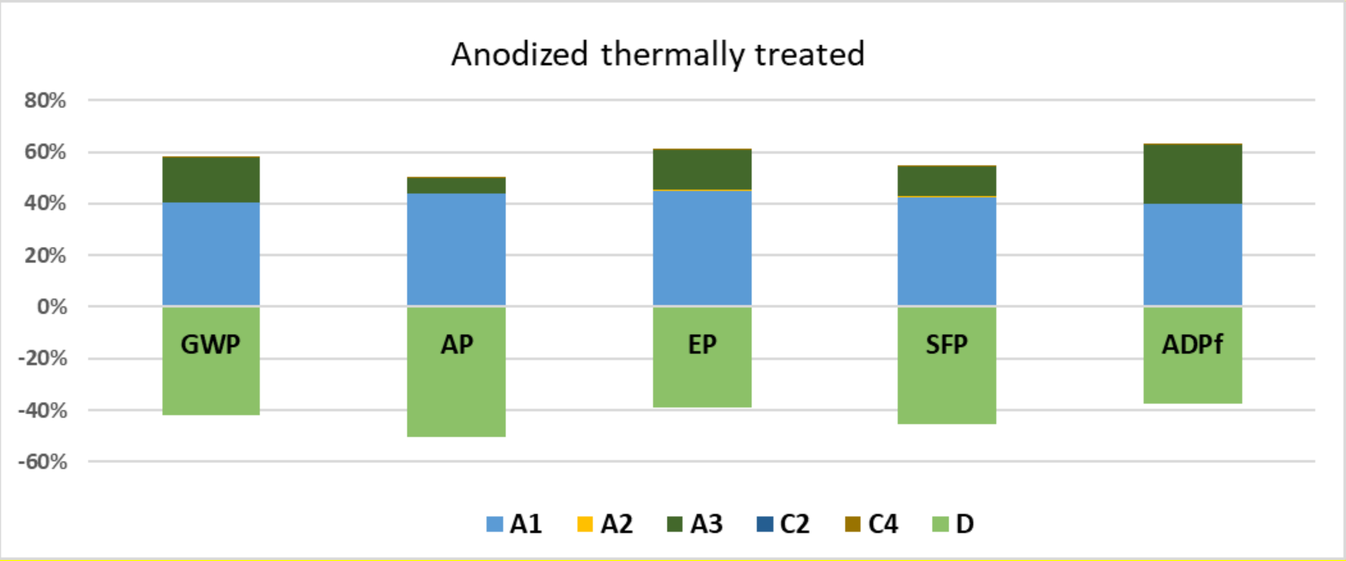


**Figure 4-4: Thermally treated anodized aluminum extrusion relative environmental impacts of all life cycle stages**

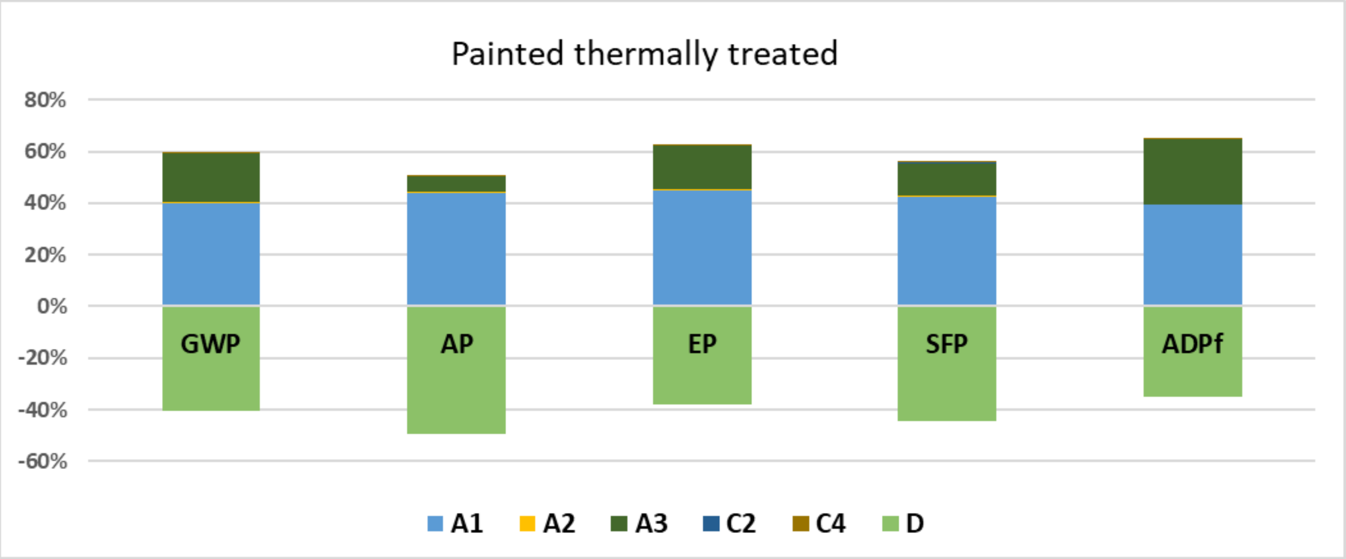


**Figure 4-5: Thermally treated painted aluminum extrusion relative environmental impacts of all life cycle stages**

## 4.3. Fabrication Contribution Analysis

To better understand the sources of potential environmental impacts within the aluminum extrusion process, relative contributions from different processing stages are presented in Figure 4-6, Figure 4-7, Figure 4-8, Figure 4-9 and Figure 4-10.

The results are broken down into the following categories: for mill-finish extrusions, the extrusion and the cast house impacts are presented separately, for the remaining products (anodized, painted, anodized thermally treated and painted thermally treated), cast house impacts are combined with the extrusion impacts.

As seen in Figure 4-1, a large proportion of the impacts associated with mill finish aluminum extrusion product is due to the primary aluminum ingots used as a raw material input to the manufacturing stages, followed by the extrusion process. These impacts are largely offset by the recycling credit (module D), representing a decrease of at least 40% across all impact categories.

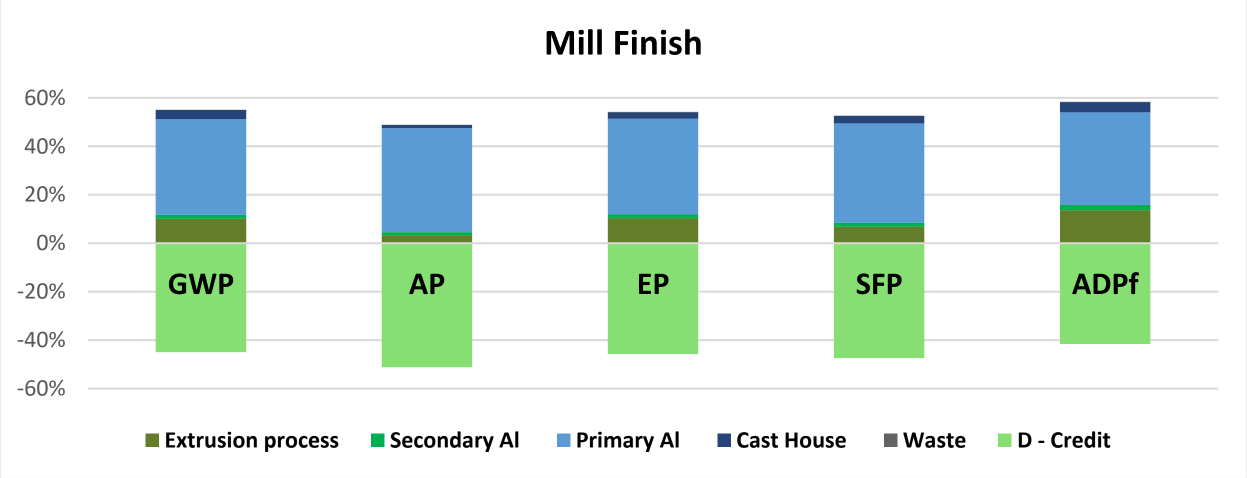


**Figure 4-6: Mill finish aluminum extrusion relative environmental impacts from different processing stages**

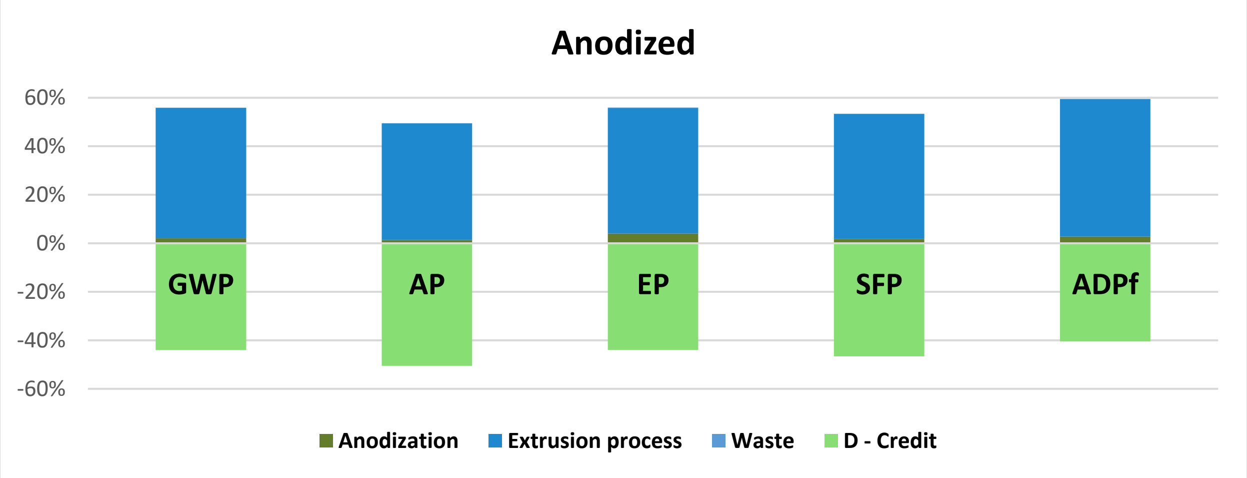


**Figure 4-7: Anodized aluminum extrusion relative environmental impacts from different processing stages**

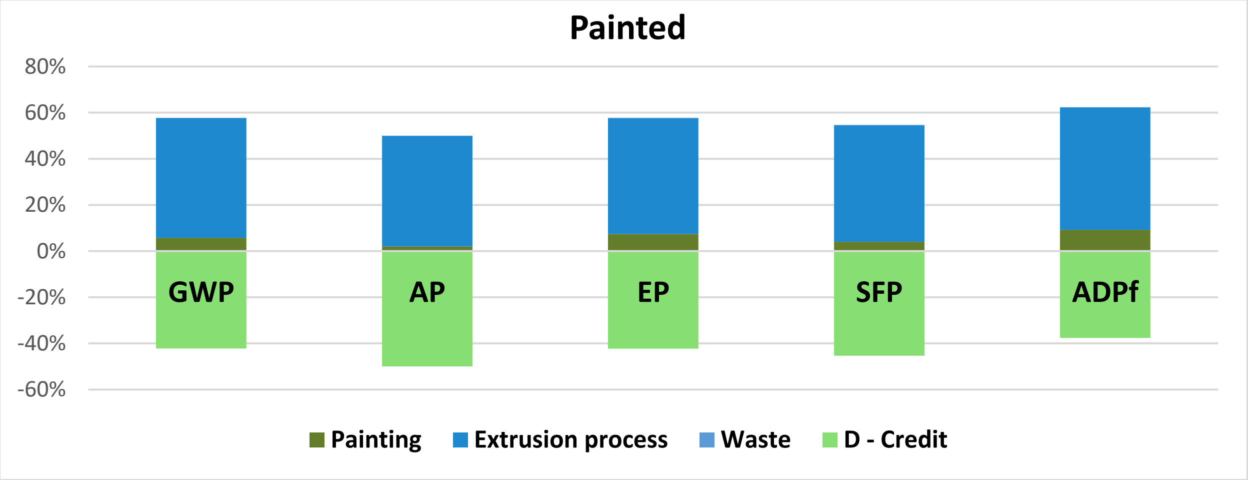


**Figure 4-8: Painted aluminum extrusion relative environmental impacts from different processing stages**

As seen in below Figure 4-9 and Figure 4-10, thermal improvement adds less than 10% to each impact category. The primary driver of the thermal improvement burdens is material inputs, both thermal break material and pretreatment material.

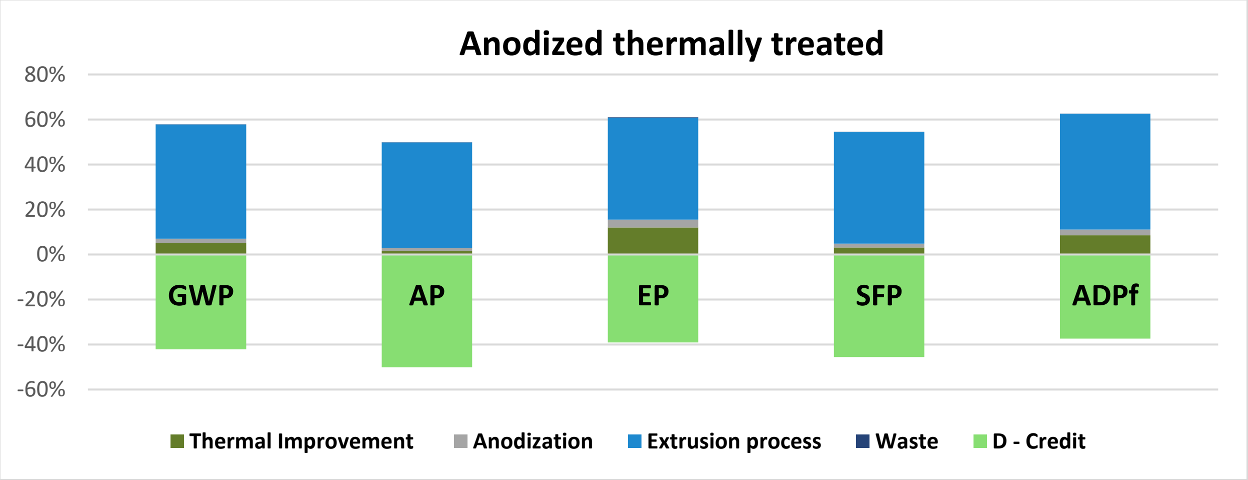


**Figure 4-9: Thermally treated anodized aluminum extrusion relative environmental impacts from different processing stages**

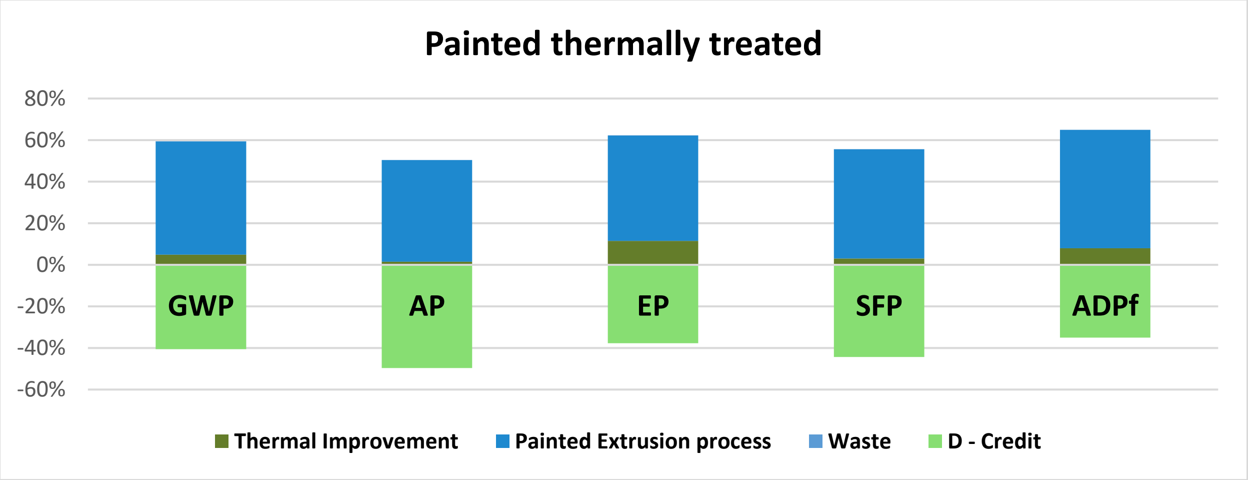


**Figure 4-10: Thermally treated painted aluminum extrusion relative environmental impacts from different processing stages**

Per the PCR, industry average EPDs are required to report information on the statistical distribution of results for all the LCIA indicators. The min and max results presented in Table 4-6 represent the facilities with the lowest (best) and highest (worst) impacts, respectively. It should be noted that, every company did not have all five unit processes (cast house, extrusion, anodizing, painting, thermal treatment). Min and max facilities are calculated for each impact category only for mill-finished extrusions. The mean and median do not take production volumes across facilities into account (i.e. it is a calculation based on each individual facility as a data point), while the weighted average presented in Table 4-1 to Table 4-5 are calculated via production volume weightings reported by each participating facility. Figure 4-11 shows the GWP distribution across all facilities.

**Table 4-6 Statistical metrics of LCIA results for 1 metric ton of extruded Aluminum (mill finish) across all facilities**

| Indicator | Unit | Min (A1-A3) | Max (A1-A3) | Max/Min Ratio (A1-A3) | Mean (A1-A3) | Median (A1-A3) |
|---|---|---|---|---|---|---|
| GWP | kg CO2 eq. | 1.47E+03 | 4.47E+04 | 3.05E+01 | 1.25E+04 | 1.12E+04 |
| ODP | kg CFC 11 eq. | 2.21E-10 | 4.60E-06 | 2.08E+04 | 4.85E-07 | 1.85E-07 |
| AP | kg SO2 eq. | 4.25E+00 | 1.28E+02 | 3.02E+01 | 4.58E+01 | 4.34E+01 |
| EP | kg N eq. | 1.55E-01 | 4.95E+00 | 3.20E+01 | 1.26E+00 | 1.11E+00 |
| SFP | kg O3 eq. | 1.11E+03 | 4.60E+04 | 4.13E+01 | 1.17E+04 | 9.35E+03 |
| $ADP_{fossil}$ | MJ, surplus | 6.30E+01 | 1.16E+03 | 1.85E+01 | 4.32E+02 | 3.93E+02 |

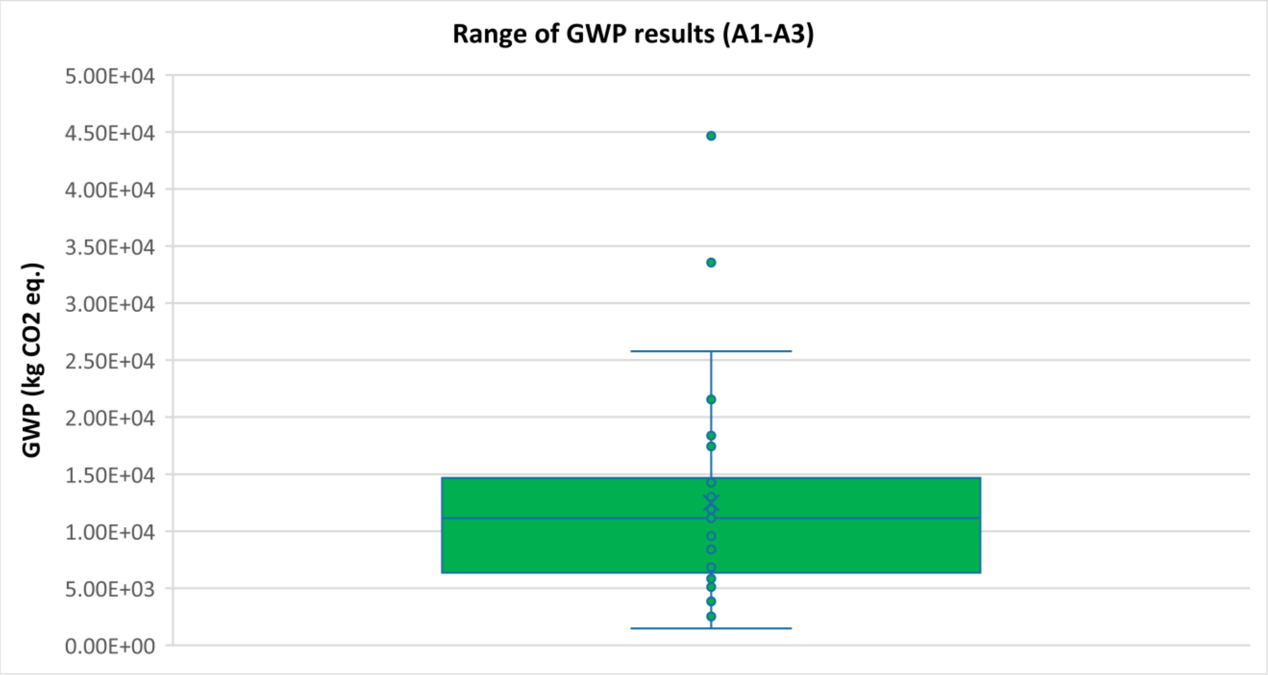


**Figure 4-11: Result variation for A1-A3 GWP across all facilities (1000 kg of mill-finished Aluminum)**

## 4.4. Sensitivity Analysis

A sensitivity analysis was conducted to examine the GWP result changes while varying of the primary and secondary aluminum composition of mill finish extrusions. It is to be noted that, all participating companies did not have cast house plant and therefore the total amount of scrap, secondary and primary aluminum coming from cast house was reported as an aggregate rather than a contribution from each individual company. A similar strategy was taken into consideration for extrusion as well to maintain the same model assumption and structure. We varied the recycled content and primary aluminum in the extrusion process maintaining the cast house as is. The results of the sensitivity on the primary and recycled contents in extrusions are shown in Figure 4-12. Please note that the ratio of primary and recycled content is limited by the amount of recycled content composition in the cast house.

A ten percent increase in primary aluminum in the mill finished product manufacturing will increase the A1-A3 GWP by ~ 1400 kg $CO_2$eq. This is equal to say that a 10% increase in recycled aluminum content will reduce the carbon footprint by the same amount.

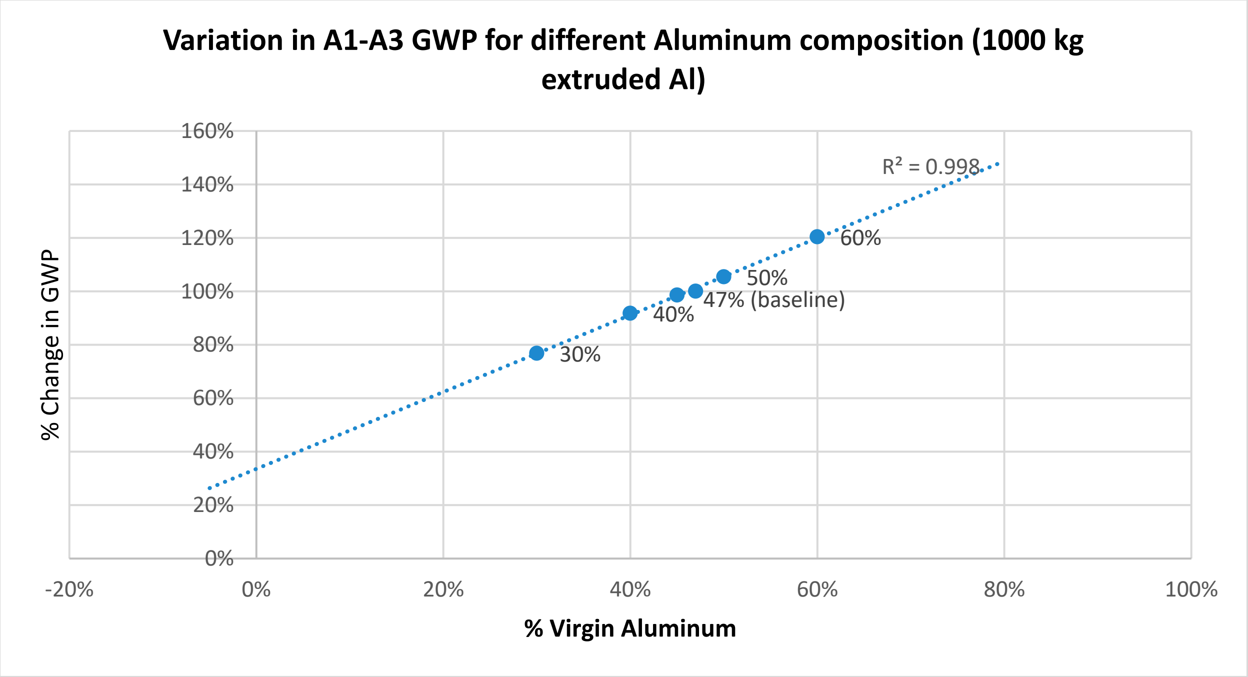


**Figure 4-12: Sensitivity analysis - Impact of primary ingot and recycled content on mill-finished Aluminum extrusions**

## 4.5. Scenario Analysis

To see the effect of primary aluminum sourcing, a scenario analysis was conducted to alternate the sourcing from different regions or countries other than the baseline case of the North American consumption mix. The metal compositions – shares of primary and recycled metal in the products, are kept unchanged for the scenario analysis.

Figure 4-13 shows the GWP changes of primary aluminum sourcing on cradle-to-gate analysis. The regions and countries included in the scenario analysis are:

RNA represents the weighted average of primary aluminum consumption mix in North America, which is the baseline case;

CA represents Canada where primary aluminum is exclusively smelted with hydropower electricity;

CN represents China where primary aluminum is mainly smelted with coal-fired electricity;

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

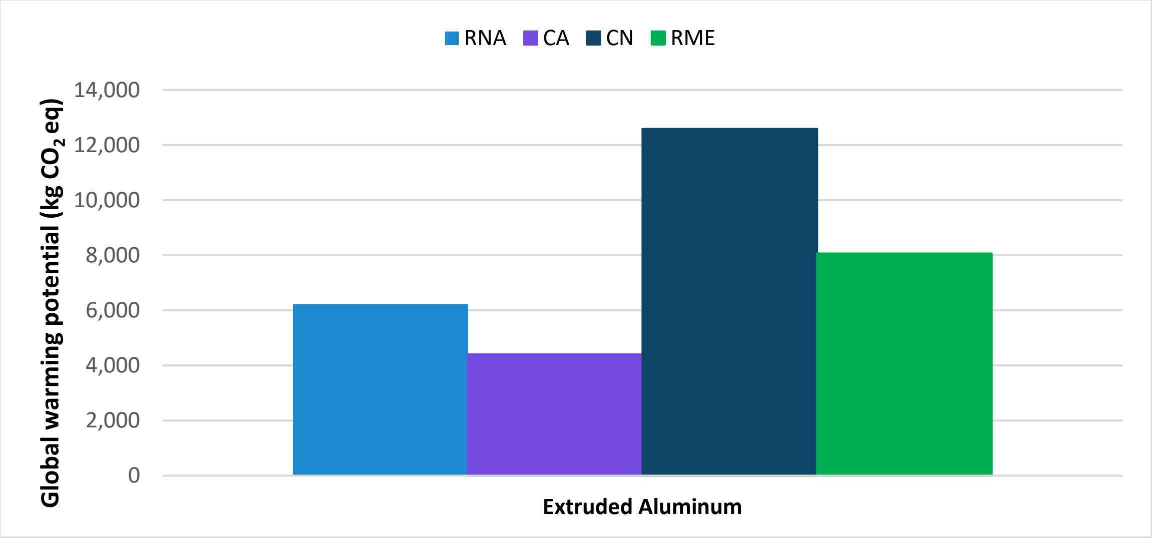


**Figure 4-13: Effect of source of primary aluminum on cradle-to-gate carbon footprint (RNA: North America, CA: Canada, CN: China, RME: Middle East)**

# 5. Interpretation

## 5.1. Identification Of Relevant Findings

For the surface treated aluminum extrusions, most of the impacts across all categories are due to the cast house and extrusions process. Surface treatments like painting and anodizing added 5% and 14% GWP impacts on top of the mill-finish extrusions. Painted thermally treated and anodized thermally treated extrusions showed a 24% and 15% GWP increase in impacts when compared to the mill finished, not thermally treated, product. Anodization showed better environmental performance than painting. Thermal treatment on top of surface treatments like painting and anodizing added approximately 10% extra in GWP impact and between an additional 13-15% to EP impacts.

These observations are also consistent across all impact categories. The primary aluminum and its transformation through the casting process are the highest contributors for all impacts categories for mill finish extrusions. All impacts categories were also largely offset by the aluminum credit given in module D.

## 5.2. Assumptions And Limitations

As discussed in Section 3.2.3, three of eight companies did not provide data for their own billet, so primary ingot was modeled using the Aluminum Association dataset, and secondary billet was modeled based on the ratio of primary ingot and aluminum scrap corresponding to the recycled content of the billet. Both primary ingot and aluminum scrap went through a remelting process. 6 of 27 total extrusions facilities were not able to provide the recycled content of their purchased secondary billet, the industry average (75%) was used.

Anodization chemicals were modeled using proxies based on the masses available in technical data sheets (TDS) and safety data sheets (SDS). In cases where these masses were incomplete, masses were estimated based on best available data and expert judgement.

For one participating company within AEC, the painting and powder coating data were collected together and the inputs and outputs (paint, water, energy, waste, product, etc.) have all been combined under the painting process to facilitate modelling and calculation. This assumption was taken to this study as both processes used the same type of paints and chemicals.

It was not always possible to distinguish intermediate flows between extrusion and the finishing steps. One example of this is packaging. To avoid double counting of packaging impacts, total packaging for all six products was aggregated in extrusion. Although packaging would typically be more intense for painted and anodized product in order to protect the surface finish.

Where the water inputs and outputs did not balance, it was assumed the difference evaporated as water vapor.

## 5.3. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated, literature, 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 ts database 2021 were used. The LCI datasets from the GaBi CUP 2021.2 database are widely distributed and used with the GaBi 10 Software system for life cycle engineering. 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.

### 5.3.1. 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. Seasonal variations and variations across different manufacturers were balanced out by using yearly averages and production-weighted averages. 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.

### 5.3.2. 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.

### 5.3.3. Representativeness

- ✓ **Temporal:** All primary data were collected for a twelve-month period during the 2020 and 2021 calendar years. All secondary data come from the GaBi database 2021 and are representative of the years 2020-2021. As the study intended to compare the product systems for the reference year 2020/2021, temporal representativeness is considered to be high.
- ✓ **Geographical:** All primary and secondary data were collected specific to the countries or regions under study. A map showing locations of companies that provided primary data is shown in Figure 5-1. Where country-specific or region-specific data were unavailable, proxy data were used. Geographical representativeness is considered to be high.

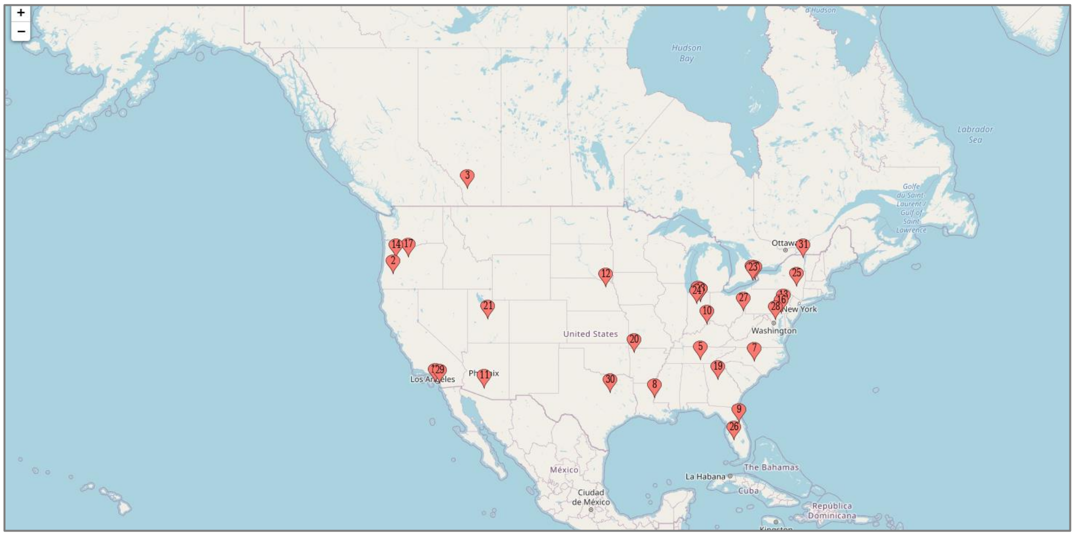


**Figure 5-1: Map indicating locations of companies that participated in the study**

✓ **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. Data was collected from the 8 participating manufacturers and is representative of AEC production.

## 5.4. Model Completeness And Consistency

### 5.4.1. 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.

### 5.4.2. 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 predominantly using LCI data from the GaBi database 2021. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

## 5.5. Conclusions And Recommendations

### 5.5.1. Conclusions

The goal of this study was to support the development and publication of EPDs for AEC's aluminum extrusions. The results of this study may also be used as an initial benchmark to track future improvements across the industry.

### 5.5.2. Recommendations

Future participants in the study should consider sub-meters in their facilities to allow for more accurate divisions of operations inputs between the extrusion and finishing process. This would reduce the assumptions required when making these divisions.

Opportunities for improving the overall impact of aluminum extrusions lie with the upstream production of aluminum. Participating companies can work to reduce their scrap rate, requiring less input of aluminum, or focus on increasing their input of secondary ingot or billet.

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