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TECHNICAL ARTICLE

# Quantifying the Carbon Footprint of the Alouette Primary Aluminum Smelter

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The Alouette primary aluminum smelter is the largest in the Americas, with an annual production of ~ 630,000 t of aluminum. In this collaborative study, a detailed product carbon footprint analysis was undertaken by Rain Carbon using a large body of primary emissions data to provide a complete cradle-to-gate analysis of the smelter's emissions. The total carbon footprint of the smelter in 2019 was 3914 kg $CO_2$e/t of aluminum for scope 1, 2, and 3 emissions, and 1835 kg $CO_2$e for scope 1 and 2 emissions. The modeling results were compared to those for global average and Canadian average smelters, using reference datasets developed by the International Aluminium Institute (IAI) and GaBi Professional Database. Alouette's carbon footprint is ~ 76% lower than a world average smelter and ~ 25% lower than a Canadian average smelter. For the scope 3 emissions, the primary contributors to the lower carbon footprint are lower emissions from the alumina supply and the calcined petroleum coke supply. Today, Alouette produces among the lowest carbon aluminum in the world, and this is set to decrease further following a switch from fuel oil to natural gas in the anode baking furnaces, and a switch to LNG at the alumina supplier refinery.

## INTRODUCTION

Primary aluminum production is an energy-intensive process, and today's smelters operate with a power consumption in the range of 12–16 kWh/kg of aluminum (direct current), depending on the electrolysis cell technology and efficiency. When power for these smelters is coal-based, total greenhouse gas emissions are substantially higher than smelters operating with renewable energy power, such as hydroelectric power. A recent paper[1] highlights the challenges faced by the aluminum industry in reducing its global GHG (greenhouse gas) footprint, given that today more than 60% of smelting capacity uses coal-based power. This paper shows a range of ~ 5–20 t $CO_2$(e) per tonne of aluminum for different regions of the world, depending on the dominant power source. The International Aluminium Institute's (IAI) website, https://international-aluminium.org/, has a large body of additional information on this subject, including a recent paper titled "Pathway to Net-Zero by 2050".[2]

With a growing focus on sustainability, the term "low carbon aluminum" is now in common use, but the industry has not settled on a standard that defines what it means. It should be noted that the term applies to a process and not to a product. A 2020 paper by the Carbon Trust[3] discusses the different approaches used by aluminum producers to label low carbon aluminum, with the most common threshold being metal produced with no more than 4 t $CO_2$(e)/t aluminum for scope 1 (direct emissions from the smelter) and scope 2 emissions (indirect emissions from power generation). Other indirect emissions (scope 3), due to, for example, upstream production of raw materials and their

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transport to the aluminum smelter, are not consistently included. For the longer term, the Carbon Trust recommends reporting scope 1, 2, and 3 emissions up to the point of metal casting at the smelter, and completely quantifying the carbon footprint from cradle-to-gate. This study supports that recommendation as the best path forward for the aluminum industry.

To highlight the different scopes included in labeling, the following provides a list of some of the trademarked names used for primary aluminum produced at renewable energy smelters with < 4 t $CO_2$e/t aluminum: REDUXA® (Hydro Aluminium, scope 1, 2 and 3), ECOLUM™ (Alcoa, scope 1 and 2), RenewAl™ (RioTinto, scope 1 and 2), ALLOW (RUSAL, scope 1 and 2), Natur-Al™ (Century Aluminum, scope 1, 2, and 3), and CelestiAl (Emirates Global Aluminium, scopes not defined). The London Metals Exchange (LME) recently (October 2021) introduced a system known as the "LMEpassport",[4] which issues electronic certificates of analysis for metal entering and leaving LME warehouses. The digital LMEpassports will allow storage of additional information on a voluntary basis, such as the carbon footprint of the aluminum.

Cradle-to-gate emissions have been estimated for smelters in the past, and examples can be found in the literature[5–8] and on the IAI website. In these previous studies and published carbon footprints, the different categories of GHG emissions (scope 1–3) are addressed differently, especially for low carbon aluminum producers. Scope 1 and scope 2 are assessed based on primary data or IAI published data.[7,8] When scope 3 emissions are included, the data used can vary between studies. For bauxite mining and alumina production, primary data or IAI data are also used. When it comes to the carbon anode, most studies rely on generic, publicly available data,[7,8] including all related upstream activities. This can lead to errors in determining the contribution of carbon anodes to the total carbon footprint. In the case of coal-fired smelters, the anode plays a minor role in terms of the total carbon footprint (< 5%), but, in the case of hydroelectric powered smelters, the production of the anode plays a more significant role (10–14%).[9]

The objective of this paper is to present the results of a detailed, cradle-to-gate product carbon footprint study for the Aluminerie Alouette smelter, in accordance with ISO 14067 using a large body of primary process data. The Alouette aluminum smelter, located in Quebec, is the largest in the Americas, with an annual production of 629,000 t in 2021. The smelter has an anode plant and produces its own prebaked anodes. It operates with hydroelectric power and has achieved industry benchmark levels of performance over its ~ 30 years of operation. The modeling work for the study was carried out by the Rain Carbon (RC) Sustainability and Life Cycle Assessment group in Germany.

Alouette receives most of its alumina from the Alunorte refinery in Brazil, which uses a combination of renewable energy power and co-generated power. RC is the main supplier of carbon raw materials to Alouette, and has extensive primary process data for production of its coal tar pitch (CTP) and calcined petroleum coke (CPC) products. Alouette is a compelling example of a smelter producing low carbon aluminum, and opportunities to lower its carbon footprint further are discussed.

## REVIEW OF CARBON FOOTPRINT STANDARDS

Currently, there are several standards with different definitions of a carbon footprint, but a more general description from the Carbon Trust[3] is: "The total greenhouse gas emissions caused directly and indirectly by a person, event, organization or product expressed as $CO_2$e". When comparing carbon footprints, different international standards have been published, which mainly focus on corporate and product carbon footprints (e.g., GHG protocol,[10] ISO 14064,[11] and ISO 14067[12]). In addition to these general standards, specific industry standards have also been developed, including The Aluminium Sector Greenhouse Gas Protocol,[13] the ASI (Aluminum Stewardship Initiative) Performance Standard,[14] and the Aluminium Carbon Footprint Technical Support Document[15]). The ASI performance standard was recently updated (May 2022), and recommends including scope 1, 2, and 3 emissions when estimating smelter GHG emissions. The terminology used in the standard is mine-to-metal GHG emissions intensity, which is line with the recommendations from the Carbon Trust, and consistent with the approach taken in this study.

A common practice when talking about GHG emissions is the concept of different scopes. Using the GHG Protocol,[10] GHG emissions are classified as per Table I. However, this concept of scopes is mostly used for reporting of carbon footprints at the corporate level. For product carbon footprints, a lifecycle stage approach is more common (from material acquisition and pre-processing to end-of-life) (Fig. 1). This is also the underlying concept of the GHG Protocol for Products, as well as the ISO standard for "carbon footprints of product" (ISO 14067[12]). The relationship of the two approaches is shown in Fig. 1.

The present study is conducted in accordance with ISO 14067,[12] and thus follows a lifecycle stage approach. However, to allow comparison with other studies, the emissions are additionally categorized as scope 1, 2, and 3. The compliance to the ISO 14067 standard for the results presented in this paper was independently verified in a critical, external review by Sphera.[17]

The Alouette primary aluminum smelter (Fig. 2) is located in Sept Iles, Quebec. The Phase I smelter was commissioned in 1992, with a single potline of

**Table I. Definition of scope 1, scope 2, and scope 3 emissions from the perspective of aluminum production**

| Scope | Definition | Examples from the perspective of aluminum production |
|---|---|---|
| 1 | Direct GHG emissions from sources that are owned or controlled by the reporting company | •Emissions from physical or chemical processing (aluminum electrolysis, anode baking)<br>•Emissions from energy generation (e.g., electricity, steam) on site through fuel combustion |
| 2 | Indirect GHG emissions associated with the generation of purchased electricity, heat or steam | •Emissions for the generation of energy purchased from third parties |
| 3 | Indirect GHG emissions that are a consequence of the activities of the reporting company, but occur from sources owned or controlled by another company | •Emissions from upstream production of raw materials used by the company (e.g., alumina, calcined petroleum pitch, coal tar pitch)<br>•Emissions from external transportation of products, materials, and waste |

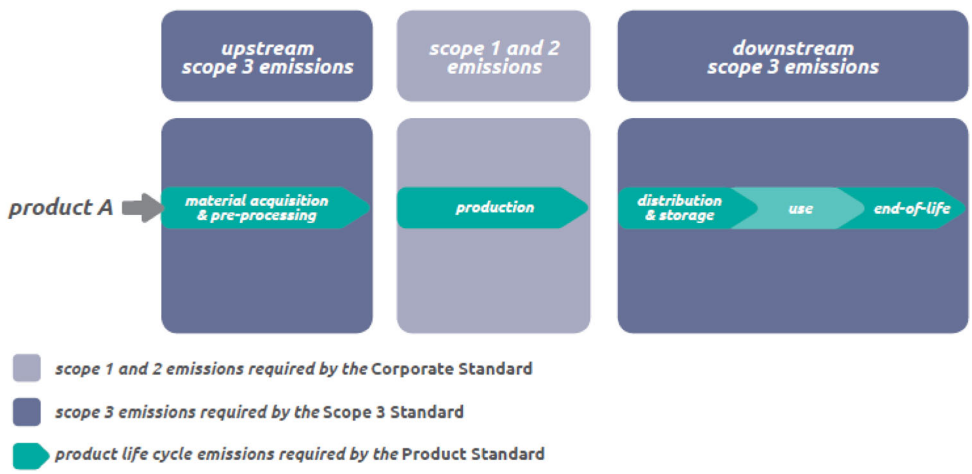



Fig. 1. Relationship between scopes in GHG reporting and lifecycle approach for product carbon footprint. Reprinted with permission from Ref 16

Fig. 2. Alouette aluminum smelter, Sept Iles, Quebec.

AP30 design electrolysis cells and an anode paste plant and baking furnace. A Phase II expansion was completed and commissioned in 2005, with a second potline of AP30 cells and a second baking furnace. The smelter is owned by a consortium of shareholders, including Austria Metall (20%), Hydro Aluminium (20%), Investissement Québec (6.67%), Marubeni Metals & Minerals (13.33%), and Rio Tinto (40%). The smelter is currently converting its electrolysis cells to an AP40 cell lining design (75% implementation by end-2021), and the full conversion will be completed in early 2023. Today, both potlines operate at 395 kA, and, since the smelter produces its own prebaked anodes, the emissions related to anode production are included in scope 1.

As part of the AP40 cell design change, Alouette installed a forced cooling network to its pot shells during the 2020/2021 period.[18] This implementation had some impact on operational stability at the smelter, so 2019 was picked as the reference year for the carbon footprint study. In 2019, the Alouette smelter operated at 384.3 kA with an average energy consumption of 13.25 DC MWh/t, a current efficiency of 91.6%, and a net carbon consumption (NCC) of 0.4215 t/t aluminum. The anodes are 1550 mm long and the cells do not have a magnetic compensating loop. The smelter uses hydroelectric power from Hydro Quebec, with a published carbon footprint of 0.0005 kg $CO_2$e/kWh.[19]

In addition to benchmark energy consumption, Alouette operates with a low overvoltage/cell/day. $CF_4$ and $C_2F_6$ are potent GHGs, and Alouette has been able to reduce those emissions by more than 30% since the smelter startup in the early 1990s. The smelter produces primary aluminum product in the form of aluminum sows, with an average weight of 750 kg. The casting operation is highly automated, with hot metal delivered to the cast house in crucibles via hot metal carriers. The sows from the casting carousel are air-cooled, which heats the building in winter and contributes to energy savings, which help reduce the carbon footprint.

The finished metal product is transported to a metal warehouse. From there, it is moved to a transition zone, and then loaded out onto vessels using conventional forklift trucks. The simple metal casting operation helps to minimize the smelter energy consumption beyond the potline operation, carbon plant, and fume-treatment systems. Remelting of sows later by end-users producing extruded products, for example, will generate additional $CO_2$ emissions compared to a smelter producing vertical direct chill billet products.

## ALUMINA RAW MATERIAL

The alumina used by Alouette is mostly sourced from the Alunorte alumina refinery in Brazil. Alunorte is the largest refinery in the world outside China, with an annual production of 6.3 million t of alumina (2021). Alunorte sources 70% of its bauxite from the Parogominas mine located in Pará State, Brazil. The bauxite is transported 244 km via a pipeline in slurry form, making it highly efficient from a GHG and sustainability perspective. The other 30% of the bauxite is sourced from the Trombetas mine operated by Mineração Rio do Norte and shipped to the refinery by bulk vessel. The alumina refinery operates with one of the lowest carbon footprints in the world for bauxite mining and alumina production, with a 2019 value of 0.71 t $CO_2$e/t alumina.

The low $CO_2$ footprint is driven by a low specific energy consumption of $\sim$ 8.0 GJ/t of alumina.[20] Factors which contribute to the low energy consumption include a favorable bauxite quality with a high alumina and low organic content, which results in a relatively high yield of alumina. The predominant mineral form in the bauxite is Gibbsite [$Al(OH)_3$], which reduces the severity and energy requirement for the caustic digestion. A significant portion (45%) of the plant's electrical energy comes from co-generation of electricity at the refinery's steam plant. The remaining electrical energy comes largely from renewable energy sources. The scale, efficiency, and stability of the refining operation also contributes to the low carbon footprint.

## CARBON RAW MATERIALS

The primary carbon raw materials used at Alouette are CTP and CPC. The CTP is sourced mainly from RC's distillation plant located in Zelzate, Belgium. A detailed overview of the CTP distillation process is provided elsewhere,[21] but the starting raw material is coal tar, which is a byproduct from the production of metallurgical coke used in the manufacture of steel via the blast furnace process. RC has detailed primary data for CTP production, and has worked closely with one of its key coal tar suppliers to gather data for coal tar production. The CTP from Zelzate is shipped to Alouette in bulk vessels, and the GHG emissions associated with the transport of CTP and all other raw materials to the smelter are included in the carbon footprint analysis.

RC is the main supplier of CPC to Alouette from its Lake Charles calcining plant in Louisiana. To simplify the carbon footprint analysis, the study assumes that all CPC used by Alouette in 2019 was sourced from this calciner. In addition to producing CPC, the Lake Charles plant produces up to 35 MW of electrical power from waste heat recovered during the calcining process. RC added a waste heat energy recovery and sulfur dioxide ($SO_2$) scrubbing system to the plant in 2013 (Fig. 3). The power produced from the steam turbine and generator is classified as renewable energy power by the State of Louisiana, since it is generated without any additional $CO_2$ emissions. In 2019, the calciner produced a total of 226,200 MWh of electrical power.

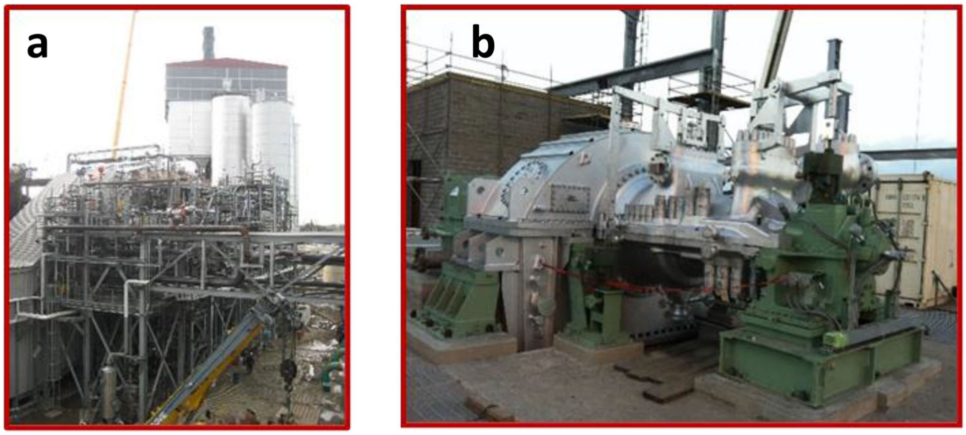



Fig. 3. Lake Charles calcining plant: (a) waste heat recovery boiler and $SO_2$ scrubber and (b) steam turbine.

Power generated by the Lake Charles calciner displaces power produced elsewhere in the Louisiana energy grid, and a $CO_2$ offset or reduction can be taken for each tonne of CPC produced. More detail on this offsetting mechanism is provided in a previous publication on RC's Visakhapatnam calciner in India.[9] The net result is that the carbon footprint of CPC produced at the Lake Charles calciner is significantly lower ($\sim$ 16%) than for CPC produced at an equivalent calciner without waste heat energy recovery.

The green petroleum coke (GPC) required to produce CPC is generated as a byproduct from oil refining. A detailed description of the GPC and CPC production processes can be found elsewhere,[22] but RC worked closely with one of its GPC refinery suppliers to obtain primary GHG emissions data for GPC production. The refinery sources crudes from multiple sources, which makes it very difficult to estimate GHG emissions associated with crude oil production. As a result of this complication, the study uses GaBi data for both crude oil and GPC production. The GaBi data for GPC production was cross-checked with the refinery supplier data to ensure consistency.

Oil refining is essentially a distillation process requiring energy to separate, and, in some cases, transform, the different hydrocarbon compounds in crude oil into a range of gaseous, liquid, and solid products. The GHG emissions associated with GPC production can be calculated reasonably well by allocating the total $CO_2$ emissions based on a mass balance and net calorific value of the refinery products. This was the approach used for the GaBi data.[23]

## OTHER KEY RAW MATERIAL INPUTS AND WASTE/BY-PRODUCTS

In addition to the consumable alumina and carbon raw materials, the Alouette smelter uses a wide range of other secondary materials. The contribution of these materials to the smelter carbon footprint is smaller than the above raw materials, but needs to be considered in a detailed cradle-to-gate analysis. A summary of some of the key secondary materials is:

- Aluminum fluoride: $AlF_3$ must be added to the cells to control and maintain bath chemistry. The annual $AlF_3$ consumption falls within the normal range for AP30–AP40 smelters.
- Fuel oil: Heavy fuel oil is combusted in the anode baking furnaces.
- Refractory materials: These are used routinely in the relining of electrolysis cells and replacement of flue walls in the anode baking furnaces. Smaller amounts are used to reline the bath and metal crucibles used in the potlines and casting operations.
- Cathode blocks: The electrolysis cells use fully graphitized cathode blocks for relining. Smaller amounts of carbon ramming paste are used between and around the cathodes.
- Iron and steel: Steel is used in a variety of areas in the smelter, for anode assemblies and stubs including cast iron, pot-shells, steel shot to clean anode butts, steelwork used in routine maintenance, and special projects etc. All used steel is sold for recycling.
- Diesel and gas: used in mobile equipment operating in and around the site.
- Spent pot lining: The cell lining waste materials recovered at the end of the cell life.

## PRODUCT CARBON FOOTPRINT MODELING

Figure 4 summarizes the input data for the modeling work. The global warming potential (GWP) was calculated using IPCC 2013[22] related to the functional unit of 1 t of aluminum. The GWP results were compared to reference data for aluminum production from the IAI. The IAI collected extensive aluminum industry data in 2015, and published this as part of a Life Cycle Inventory Data

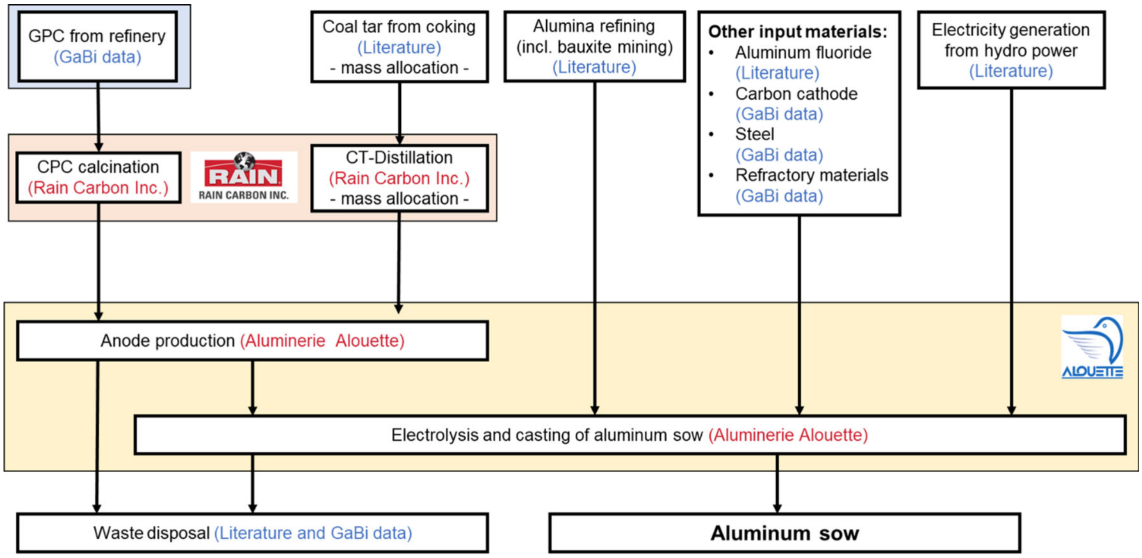



Fig. 4. Data inputs for Alouette product carbon footprint modeling.

report in 2017.[7] As discussed in Sect. Comparison of Alouette Smelter Footprint to Modeled Reference Smelters, the reference data were corrected after an error was discovered in the carbon consumption data.

The study is based on 2019 primary data from the Alouette smelter and Rain Carbon. For bauxite mining and alumina refining, data were provided by Alouette's alumina refinery supplier. Secondary data from the literature and GaBi Professional database (v.CUP 2021.1)[23] were used for all other upstream and downstream processes.[24] Literature and GaBi data were used for waste recycling,[23,25–27] including the modeling of credits for the use of secondary raw materials, such as spent pot lining in the cement industry.[27] Additionally, data from the GaBi Professional database[23] were used for the transport of raw materials, electricity generation, and carbon cathode production.

Some assumptions needed to be made for selected upstream processes. The production of aluminum fluoride from hydrogen fluoride and aluminum hydroxide[28] was based on stoichiometric calculations and generic data on energy consumption.[29] The production of the carbon cathode assumed a similar baking process to anode production.[30] Due to missing data, further processing by graphitization was not considered, but is expected to have only a minor impact on the final carbon footprint.

Allocation was avoided for the CPC, anode, and aluminum production, as shown in Fig. 4, by including all outputs and, if necessary, through a system expansion. The coke oven process, coal tar distillation, and refinery operation for GPC production are all multi-output processes. As a result, process outputs differ in their intended use, and, to address this, a mass allocation was applied for the coke oven process and coal tar distillation. GPC production has been based on the GaBi refinery model, with crude oil consumption allocated by net calorific value and emissions allocated by mass.

## DISCUSSION

### Smelter Carbon Footprint

The carbon footprint of aluminum production at Alouette and the related supply chain (scope 1, 2, and 3) is shown in Fig. 5, and totals 3914 kg $CO_2$e/t Al. Considering only scope 1 and 2 emissions, the carbon footprint is significantly lower at 1835 kg $CO_2$e/t Al. The scope 1 emissions from the smelter process (which includes $CO_2$ emissions from anode consumption, perfluorocarbon emissions, anode production, and anode baking $CO_2$ emissions, and casting-related $CO_2$ emissions) account for $\sim$ 47% of the total emissions. The next largest contribution comes from alumina production and bauxite mining at 35%.

Anode production and related upstream production of CPC and CTP contributes 20% to the overall carbon footprint (anode baking 5%, CPC production 13%, and CTP production 2%). The upstream CPC production has the largest share of this. The process emissions from calcination (50%) and GPC production at the refinery (37%) are the largest contributors (Fig. 6a). The data show that it is possible to significantly reduce the carbon footprint of CPC by adding waste heat recovery systems which export power to the local power grid. The waste heat recovery system at the Lake Charles calciner reduces the overall carbon footprint by $\sim$ 16% to 516 kg $CO_2$e/t Al. As noted earlier, an assumption was made that all the CPC was supplied by the LC calciner in 2019, to simplify the modeling work. Over the last 2 years, the percentage has varied between $\sim$ 80 and 100%, and any CPC supplied

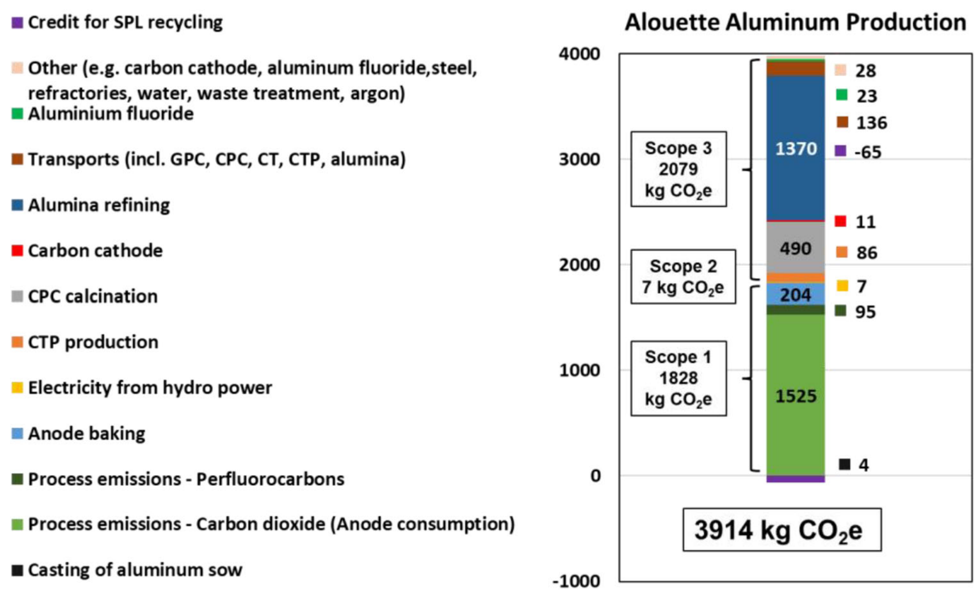



Fig. 5. Breakdown of the carbon footprint for the Alouette smelter.

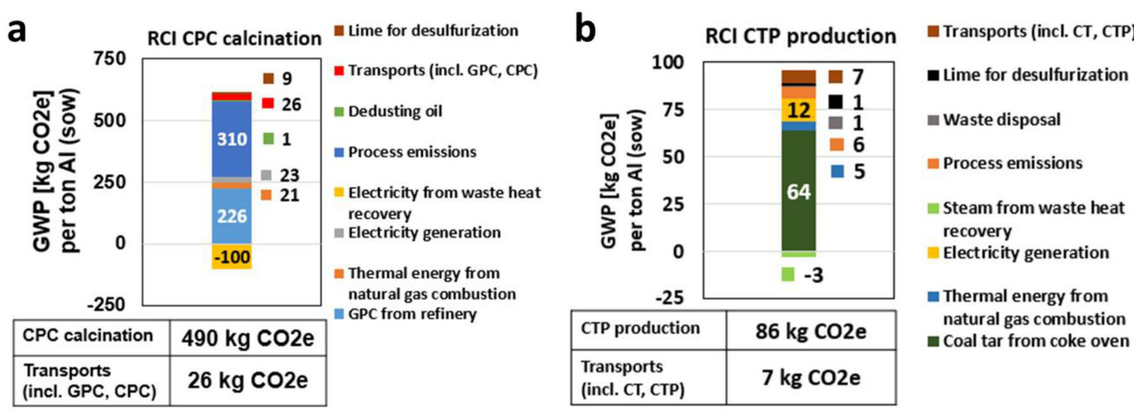



Fig. 6. Breakdown of the carbon footprint for (a) CPC calcination and (b) CTP production.

from a calciner without waste heat recovery will increase the smelter carbon footprint somewhat. Compared to CPC, CTP makes only a minor contribution to the carbon footprint. The upstream CTP production (Fig. 6B) is dominated by the coal tar (68%) raw material.

Electricity generation from the smelters hydroelectric power (0.2%) and transportation of raw materials (3%) have a minor impact on the carbon footprint, as do all other raw material inputs and their associated upstream emissions. Casting-related emissions are also very low as a result of the simple casting operation at Alouette. Hot metal from the potlines is cast directly into preheated sows, after Alouette shut down its holding furnaces several years ago. The only emissions today are from sow preheating, and these are included in Fig. 5.

In summary, scope 1 emissions (47%) and scope 3 emissions (53%) have the largest impact on the overall carbon footprint at Alouette, whereas scope 2 emissions (0.2%) have a negligible impact.

## Comparison of Alouette Smelter Footprint to Modeled Reference Smelters

One of the goals of this study was to compare the results of modeling work using a large body of primary data with the results of studies conducted with IAI data[7] available from databases like the GaBi Professional database. This has been the approach of previous studies cited earlier in the paper. When the Alouette smelter data were compared in more detail with the IAI reference smelter operating in Canada, the Alouette smelter showed a higher (~ 9%) carbon footprint for anode production. This was unexpected, given Alouette's favorable NCC and gross carbon consumption (GCC) figures. This prompted a closer look at the model output from the IAI/GaBi reference dataset.

**Table II. Carbon consumption results for the Canada reference smelter before and after corrections**

| | Canada reference | Canada reference (corrected) |
|---|---|---|
| CPC consumption/t Al [kg] | 279 | 346 |
| CTP consumption/t Al [kg] | 62.3 | 77 |
| Recycled butts/t Al [kg] | 82.3 | 136 |
| Gross carbon consumption/t Al [kg] | 423 | 559 |
| Net carbon consumption/t Al [kg] | 341 | 423 |
| Butts recycling rate [%] | 19 | 24 |

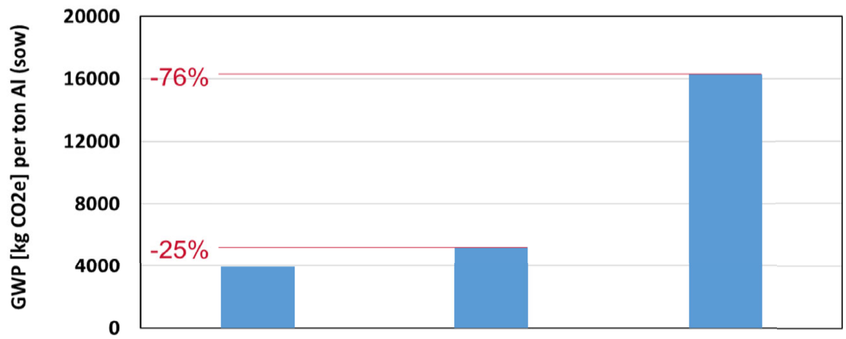
A significant error was found at this point for the NCC and GCC, which had a major impact on the upstream CPC and CTP consumption. The second column in Table II shows the model output for the Canadian reference smelter for NCC, GCC, CPC consumption, CTP consumption, and butts consumption. The NCC is equal to the tonnes of baked anodes (carbon) consumed electrolytically, including excess consumption (see below). The NCC does not include the anode recycle material or butts sent back to the anode plant. The GCC is equal to the total tonnes of baked anodes (carbon) sent to the electrolysis cells. The baked anodes contain a portion of recycled anode butts.

The theoretical consumption of carbon per tonne of aluminum for the Hall–Heroult electrolysis process assuming 100% current efficiency is 334 kg/t aluminum. The actual consumption is always significantly higher than this, due to current efficiency losses and excess carbon consumption. The excess consumption is due to the reaction of the carbon anode with $CO_2$ generated during electrolysis and oxygen from air, which comes into contact with the top of the hot anodes during electrolysis, and when the hot anode butts are removed and cooled.[31] Today, the best cells in the world achieve a NCC of ~ 395 kg/t aluminum but the typical range is 400–450 kg. The NCC of 341 kg/t Al for the Canadian reference smelter shown in Table II is therefore not possible, and represents an error in the reference dataset. The GCC value of 423 kg/t Al for the Canada reference smelter in Table II is much closer to the NCC expected for a modern prebake smelter, and very close to the 421.5 kg actual value for Alouette. It therefore looks like a NCC value was used instead of a GCC value at some point during the dataset compilation.

This error has been communicated to Sphera (provider of the GaBi Professional database) and the IAI,and can be found in the data appendix of the 2017 IAI life cycle inventory report.[7] It is expected to be corrected in early 2023 when the GaBi datasets are updated. The impact of the error is that it causes an underestimation of the tonnes of anodes required for production at the smelter, which in turn underestimates the tonnes of CPC and CTP consumed. The data were corrected for this study, and the revised model data are shown in column 3 of Table II for the Canadian reference smelter.

When the corrected values for the NCC and GCC are used, the CPC and CTP consumption for the reference smelter increases to levels very close to the actual CPC and CTP volumes used by Alouette in 2019. The GCC is also within 2% of the Alouette GCC. Using this corrected data, Fig. 7 shows the total Alouette carbon footprint compared to a global average reference smelter and a Canadian average reference smelter using the GaBi/IAI dataset. The Alouette carbon footprint is 76% lower than the global average and 25% lower than the Canadian average. The large difference between the global smelter average and the Canadian and Alouette smelter carbon footprints is driven by the difference in scope 2 emissions associated with power generation. All Canadian smelters use hydroelectric power, whereas only ~ 30% of global aluminum smelters use hydroelectric or other forms of emissions-free power, like nuclear. The difference between the Alouette smelter carbon footprint and the Canadian reference smelter is due to differences in technology, performance, and raw material supply chains. The Alunorte refinery supplying most of Alouette's alumina, in particular has a significantly lower GHG intensity compared to industry averages.

Table III shows the re-calculated anode carbon footprint for the Canadian reference and global reference smelters compared to the Alouette smelter. The Alouette data for CPC and CTP in this table include the transport-related emissions shown in Fig. 6. The total anode carbon footprint for the Alouette smelter is ~ 13% lower than the Canadian reference smelter, and ~ 21% lower than the global average reference smelter. The biggest contributors to these lower carbon footprints are the CPC production and anode production. The most significant driver of the lower CPC carbon footprint is the waste heat recovery and energy generation at RC's Lake Charles calciner. The electricity generated from waste-heat is considered an emission-free by-product, and leads to the avoidance of emissions by alternative energy generation. A conventional calciner without waste heat recovery, as accounted for in the reference data, shows a higher carbon footprint (Table III).




| | Alouette Smelter | Reference 1 Canada Average | Reference 2 Global Average |
|---|---|---|---|
| kg $CO_2$e / t Al (sow) | 3914 | 5230 | 16300 |

Fig. 7. Comparison of carbon footprint: Alouette smelter versus reference smelters.

**Table III. Smelter and anode carbon footprint using the corrected dataset**

| Carbon footprint aluminum [kg $CO_2$/t Al] | Alouette/RCI | Ref. Canada (corrected) | Ref. global (corrected) |
|---|---|---|---|
| Total for smelter | 3914 | 5230 | 16,300 |
| CPC | 516 | 560 | 612 |
| CTP | 93 | 105 | 111 |
| Anode production (excluding raw materials) | 204 | 266 | 303 |
| Total anode carbon footprint | 813 | 931 | 1026 |

The anode production-related emissions at Alouette are also significantly lower than the Canadian reference and global average reference smelters. This is due to the efficient operation of the Alouette baking furnace, in terms of fuel consumption and lower CTP consumption, also contributing to this. Another potential contributor to differences between the Alouette carbon footprint and the reference smelter footprint may be the literature data used in this study, which may be incomplete in some areas. As an example, the $CO_2$ emissions associated with producing fully graphitized cathodes are likely to be understated, since the final graphitization step was not included in the literature data. The impact of this will be small, however, given that overall emissions for a hydroelectric powered smelter are dominated by the smelter process emissions, alumina supply, and anode production, including CPC and CTP.

## FUTURE GHG IMPROVEMENT POTENTIALS AT ALOUETTE

Alouette's product carbon footprint is set to decrease even further over the next several years. The first reduction will come in 2022, when Alouette switches the anode baking furnace fuel source from heavy fuel oil to natural gas. The change is expected to reduce the baking furnace $CO_2$ emissions by 30%, since $CH_4$ has a higher heat content due to the higher hydrogen content versus heavy fuel oil. Alouette is targeting another improvement in the coming year, when the smelter will have rebuilt its oldest (Phase 1) anode baking furnaces. The smelter is still operating the original furnaces and, although these have been well maintained, a reduction in energy use to $< 1.8$ GJ/t is expected when the rebuilds are complete. Other reduction initiatives will emerge in the future, as Alouette has committed, at the launch of the celebrations of its 30 years of operation, to achieve carbon neutrality by 2050.[32]

The Alunorte alumina refinery has already reduced its carbon footprint further from the 0.71 value achieved in 2019, and used in this study. In 2021, the refinery's carbon footprint was 0.63 t $CO_2$/t alumina, including bauxite mining.[33] In 2019, the refinery was restarting some capacity after a partial curtailment in 2018, and this contributed to some inefficiencies relative to the refinery operating at full rates. Another significant improvement will be realized in 2023, when the refinery switches from fuel oil to liquid natural gas (LNG). This will reduce $CO_2$ emissions from the refinery by $\sim$ 700,000 t/year, which will equate to a reduction of $\sim$ 127,000 t $CO_2$/year from the alumina supply chain.

RC has undertaken a detailed feasibility study to explore a CCUS (carbon capture usage and storage) solution to remove $CO_2$ from its Lake Charles calciner. The study was based on using commercially available $CO_2$ removal technology, based on adsorption by aqueous alkanolamine solutions.[34] For the full calciner operation, this would require removal of $\sim$ 360,000 t of $CO_2$/year. The calciner is located close to a $CO_2$ pipeline running through the US Gulf coast region and Lake Charles area. The capital and operating costs of adding CCUS technology to the calciner is prohibitively expensive today (> US$160 million capital cost), even though the project would qualify for 45Q tax credits.[35] If these credits increase significantly or an aggressive carbon pricing policy is adopted by the US Government, the situation may change over the longer term. The development of more efficient CCUS technologies could also help this situation.

## CONCLUSIONS AND RECOMMENDATIONS

The Alouette smelter operates with one of the lowest carbon footprints in the world and produces a primary aluminum product with cradle-to-gate emissions of 3.9 t $CO_2$e/t for scope 1, 2, and 3 emissions, and 1.8 t $CO_2$e/t aluminum for scope 1 and 2 emissions. Both of these are below the 4.0 t $CO_2$e/t aluminum threshold used widely throughout the industry to qualify as low carbon aluminum. While some smelters today include only scope 1 and 2 emissions in their low carbon aluminum products, the industry is moving rapidly towards a standard where scope 1, 2, and 3 emissions are included.

Much of the data used in this study is based on primary emissions data generated from aluminum and anode production at Alouette, bauxite mining and alumina refining from Alunorte, and CPC and CTP production from Rain Carbon. The total cradle-to-gate product carbon footprint is $\sim$ 76% below IAI's global average and $\sim$ 25% lower compared to reference data from the IAI for a Canadian smelter. This is due to differences in the specific raw material supply chains for Alouette, as well as differences in smelter performance. Significant errors were found in the net and the Ross anode carbon consumption data used in the reference dataset, but these have been corrected to generate the above comparisons. These errors highlight the importance of thoroughly vetting the validity of data from databases where no primary data are available.

After smelter process emissions (42%) and alumina production (35%), the production of carbon anodes contributes $\sim$ 20% to the total smelter carbon footprint. The CPC supplied to Alouette is produced at a Rain Carbon calciner operating with waste heat energy recovery and $SO_2$ scrubbing. The energy recovery from waste heat recovery reduces the carbon footprint of the CPC by $\sim$ 16%, which is a significant benefit. The CTP is produced in a modern, state-of-the art distillation plant, which sources coal tar from coke ovens in Europe operating with high efficiency and strict environmental and safety controls.

The hydroelectric power supply used by Alouette generates almost no $CO_2$ emissions, and the smelter process emissions are at low levels due to the stable operation of Alouette's AP40 prebake cell technology. Alouette also uses some of the lowest $CO_2$ alumina in the world, and this is set to decrease even further when the Alunorte refinery switches to using LNG in early 2023.

## CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

## OPEN ACCESS



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