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WHITEPAPER

# Decarbonizing Aluminum:

## Technologies and Approaches to Achieve Zero-Carbon Aluminum

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# Table of Contents

# Abstract

Aluminum is a foundational material for the clean energy transition, but the production of aluminum is very emissions intensive. Aluminum production currently accounts for 3 percent of global greenhouse gas (GHG) emissions, mainly due to its large consumption of electricity.[1] As demand for goods like electric vehicles and solar panels rises in the coming decades, aluminum demand and its corresponding GHG emissions will also rise in the absence of any action. Deep decarbonization of the aluminum sector will be needed for the United States and the world to stay on track to meet climate targets.

# Introduction

To meet global climate targets, rapid and deep decarbonization of all sectors of the economy is necessary. Many decarbonization solutions—such as electrification of transportation, expansion of the electrical grid, and renewable electricity generation—require aluminum as a material input. As a result, aluminum demand is expected to dramatically increase in the coming decades as the clean energy transition progresses.

At the same time, aluminum production is a significant source of both GHG emissions and toxic pollution. Aluminum smelting is incredibly electricity intensive: a single smelter can use the same amount of power as a midsize city. Smelters require near continuous electricity access, which clean energy is not yet equipped to provide; this means that most smelters in the United States and abroad are powered by fossil energy. Additionally, the current method for smelting aluminum involves an electrochemical reaction that releases air and water pollutants. Alumina, the precursor to aluminum, is produced through high-temperature refining, which also burns fossil fuels and releases GHG emissions and toxic pollution.

Many technologies and approaches in various stages of commercialization exist to reduce GHG emissions and pollution from the aluminum industry. Some of them can be deployed now, whereas some need more time and investment to fully realize. The scale of investment needed is massive: **the Department of Energy (DOE) estimates that decarbonizing the domestic aluminum industry will require $10 to $15 billion in capital investment through 2050.**[2] Globally, the primary aluminum sector could require $1 trillion in investment to reach net zero by 2050.[3] Given the scale of the investment needed, and the fact that many technological solutions for aluminum decarbonization are pre-commercial, supportive policies will be necessary to rapidly develop, deploy, and commercialize decarbonization technologies and strategies.

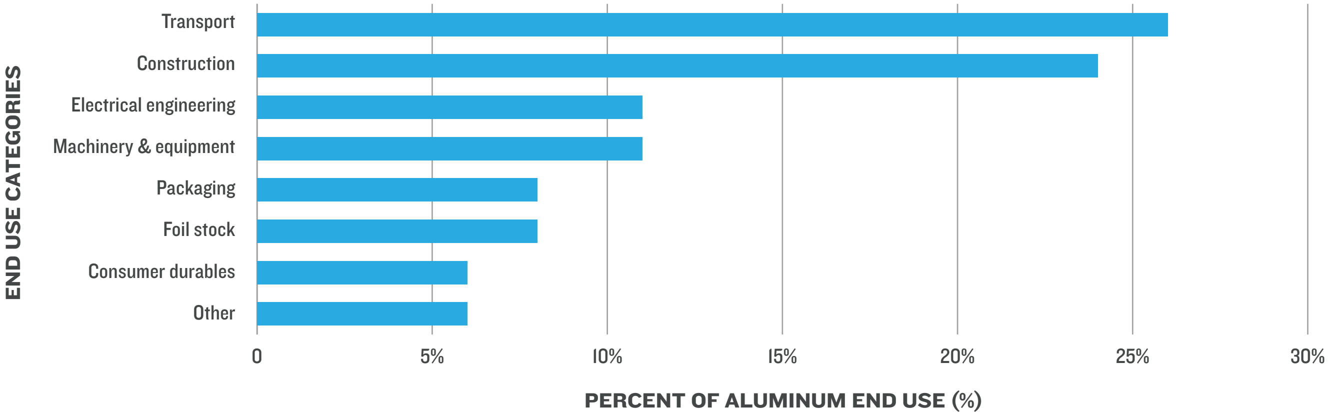
This whitepaper will describe the technological and process-innovation pathways that have the potential to reduce or eliminate GHG emissions from the production and recycling of aluminum. The paper is divided into four parts. The first will discuss the effect of the clean energy transition on demand for aluminum, the second will examine the decarbonization solutions for primary aluminum production, the third will examine solutions to improve the circularity of secondary (recycled) aluminum production, and the fourth will discuss the domestic policy levers needed to accelerate the development and deployment of these technologies and process innovations that will decarbonize aluminum.

# Global Demand for Carbon-Intensive Aluminum Is Increasing Due to the Clean Energy Transition

Aluminum has many different end uses in various markets, such as transportation and packaging (Figure 1). Aluminum usage will change and expand within these categories as other sectors of the economy decarbonize (Figure 2). By 2050, global demand for primary (virgin) and secondary (recycled) aluminum could increase between 80 percent and 290 percent, from 86 Mt (million metric tons) of demand in 2020 to 154 Mt or 335 Mt in 2050 (Table S1).[4] Factors driving this demand growth include urbanization, increased electric vehicle production, clean technology growth, electric grid expansion, and replacement of single-use plastics in packaging.[5] In a scenario where global demand grows to 298 million metric tons per annum (Mtpa), global annual primary aluminum production may need to increase by 90 Mt or, under increased aluminum recycling scenarios, by 75 Mt from a 2020 baseline of 65 Mt.[6] Regardless, aluminum production will need to significantly increase to meet expected demand in the coming decades.

**FIGURE 1: GLOBAL END USES OF ALUMINUM, 2019**

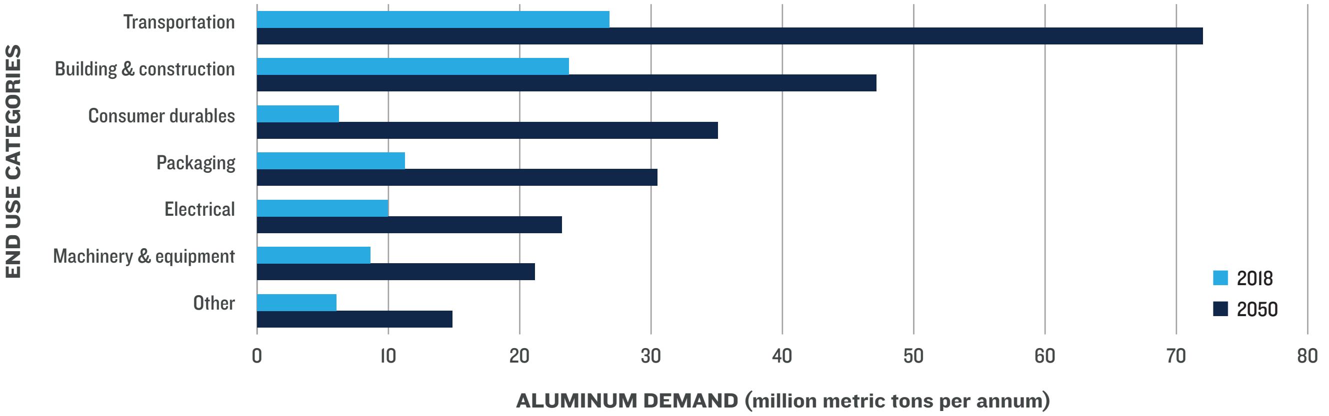
Transport accounted for more than a quarter of global aluminum end use in 2019.



*Source:* World Economic Forum, *Aluminium for Climate: Exploring Pathways to Decarbonize the Aluminium Industry,* November 2020, 9, www3.weforum.org/docs/WEF_Aluminium_for_Climate_2020.pdf.

**FIGURE 2: PROJECTED GLOBAL ALUMINUM DEMAND BY END USE, 2018 VS. 2050**

Aluminum demand could at least double in all end use categories from 2018 to 2050.



*Source:* CM Group, *An Assessment of Global Megatrends and Regional and Market Sector Growth Outlook for Aluminum Demand*, February 2020, 18–19, https://international-aluminium.org/wp-content/uploads/2021/03/cm_2050_outlook_for_al_demand_20200528_4wycD18.pdf.

The large projected increase in aluminum demand presents a climate challenge because aluminum production is very carbon intensive. In 2021, global aluminum production accounted for 1.1 billion metric tons of $CO_2$, or about 3 percent of global $CO_2$ emissions.[7] In 2021, the global carbon intensity of aluminum was 16 tons of $CO_2$ per ton of primary aluminum (Table S2).[8] In a scenario of global aluminum production growth to 298 Mt by 2050 without any decarbonization actions taken, emissions from the aluminum sector will grow 30 percent.[9] Reducing emissions from aluminum production would multiply aluminum's positive impact in a clean energy transition.

Increased production of carbon-intensive aluminum will not only lead to more GHG emissions, but it will also lead to an increase in associated toxic waste and pollution. Aluminum production is a large source of industrial waste, including red mud (an extremely alkaline waste product that can poison groundwater and contaminate rivers and ecosystems) and criteria air pollutants, such as $SO_2$ and $NO_x$.[10] Some of this pollution can be addressed through decarbonization measures (such as electricity decarbonization), but some of the pollution will likely need to be addressed independently.

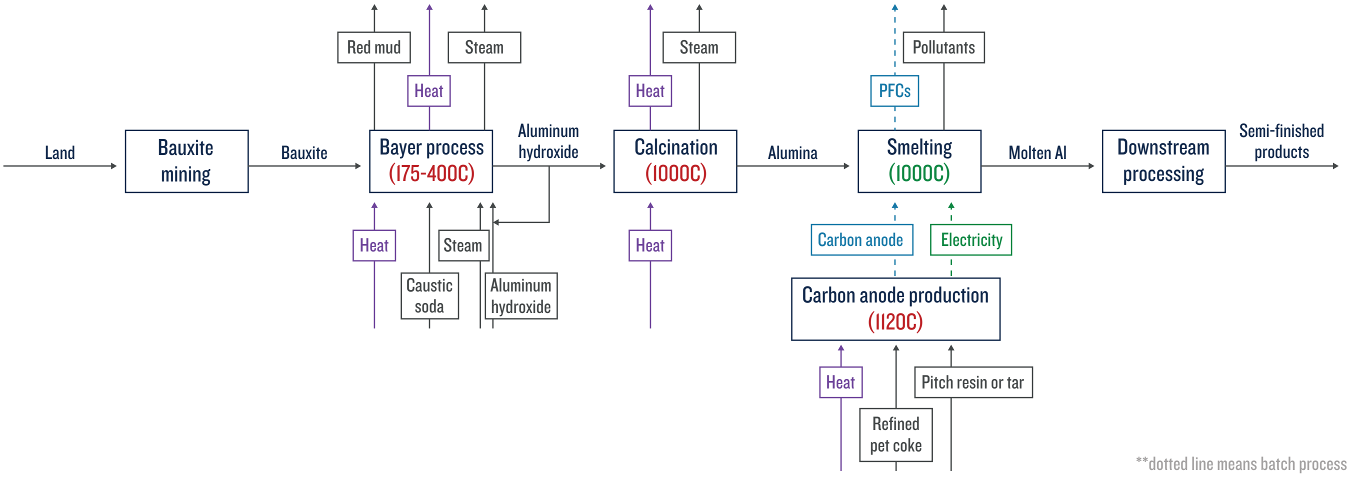
Decarbonizing the global aluminum industry will not be easy. However, the looming growth in demand for aluminum underscores the urgency with which the sector must be decarbonized.

# Decarbonizing Primary Aluminum Will Require Multiple Technology Solutions

Technologies and approaches either exist or are under development to minimize the carbon intensity and pollution impacts of aluminum production. However, they will require massive amounts of investment to scale up.

Globally, 70 Mt of primary aluminum was produced in 2023.[11] Primary aluminum is produced by first refining bauxite ore (a rock made of aluminum-containing minerals) into alumina (the common name for aluminum oxide, $Al_2O_3$), and then using electricity to break the aluminum-oxygen bonds to produce pure aluminum in a process called smelting (Figure 3). Most emissions from the aluminum sector are the result of primary production. Refining and smelting alone account for over 90 percent of GHG emissions from total aluminum production (Figure 4a). Smelting is

**FIGURE 3: BLOCK FLOW DIAGRAM DEPICTING THE GENERAL PRIMARY ALUMINUM PRODUCTION PROCESS**



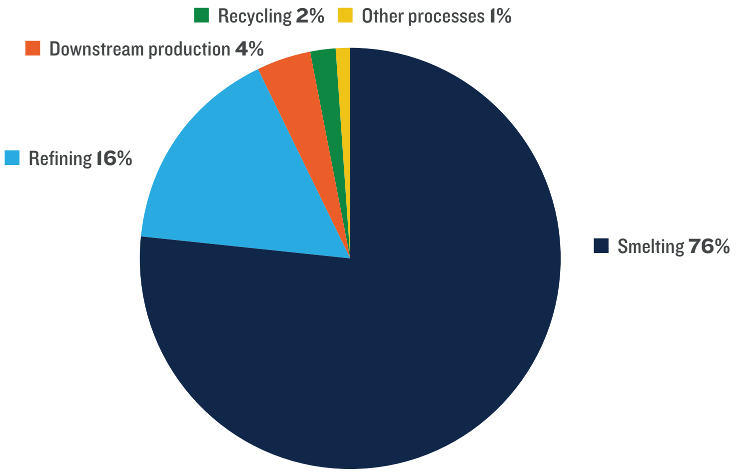
**dotted line means batch process

*Source:* Eva Rosenberg, "Aluminium Production," International Energy Agency Energy Technology Systems Analysis Programme Technology Brief, March 2012, 1-2, https://iea-etsap.org/E-TechDS/PDF/I10_AlProduction_ER_March2012_Final%20GSOK.pdf; International Aluminium Institute, "Production Process: Anode Production," The Aluminium Story, Primary Production, accessed August 14, 2024, https://thealuminiumstory.com/primary-production/anode-production/; Deloitte, *A Roadmap for Decarbonising Australian Alumina Refining*, November 2022, 11, 24, https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf.

the most emissions-intensive process, due to high electricity consumption, followed by refining, due to heat requirements (Figure 4b). Each step has multiple decarbonization solutions available at different stages of commercialization. This section discusses each step in the primary aluminum production process and the decarbonization options potentially available for them (Figure 5).

**FIGURE 4A: GLOBAL ALUMINUM PRODUCTION GHG EMISSIONS BREAKDOWN, 2022**

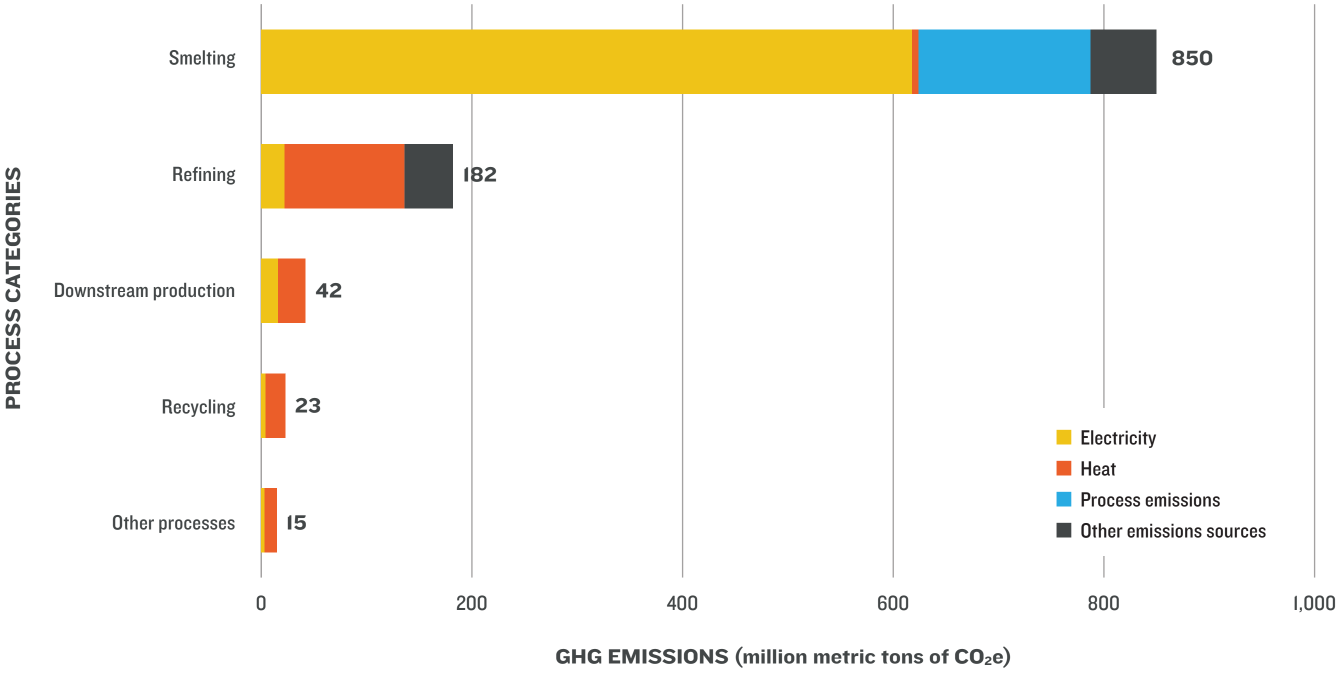
Smelting is the most emissions-intensive step, followed by refining.



*Source:* International Aluminium Institute, “Greenhouse Gas Emissions – Aluminium Sector,” January 25, 2023, https://international-aluminium.org/statistics/greenhouse-gas-emissions-aluminium-sector/.

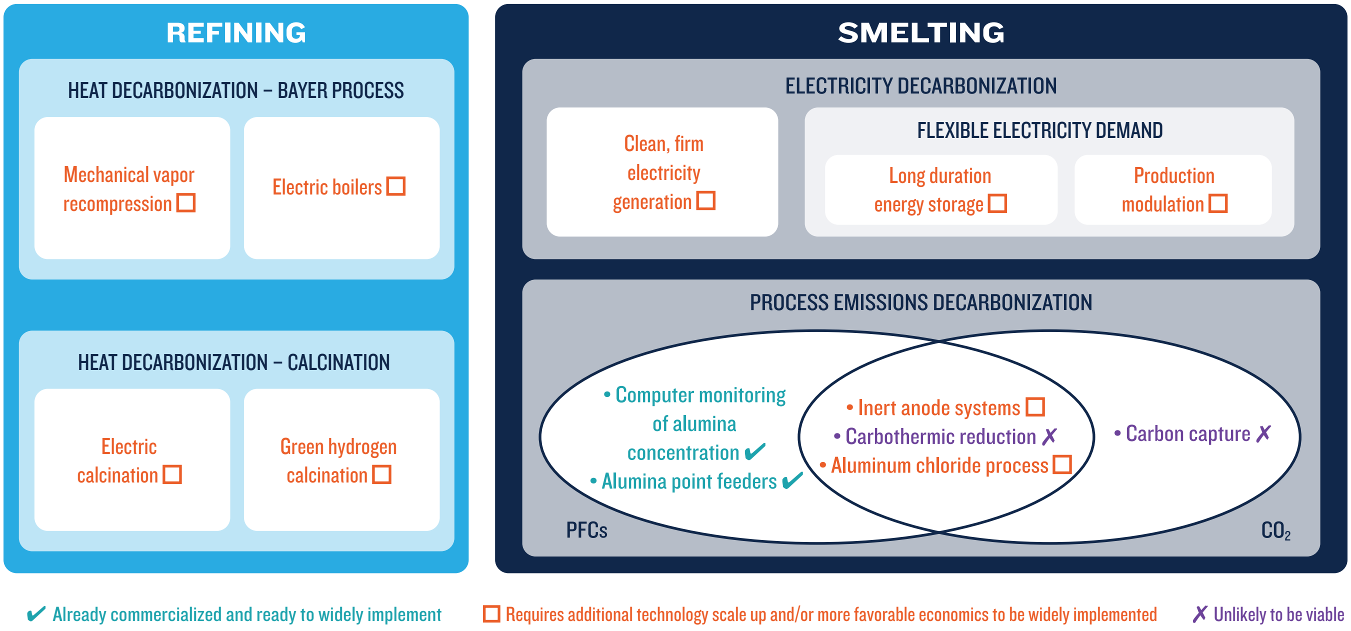
**FIGURE 4B: GLOBAL ALUMINUM PRODUCTION GHG EMISSIONS BREAKDOWN, 2022**

Smelting is the most emissions-intensive process, mostly due to large emissions from electricity consumption.



*Source:* International Aluminium Institute, “Greenhouse Gas Emissions – Aluminium Sector.”

**FIGURE 5: SUMMARY OF DECARBONIZATION LEVERS AVAILABLE FOR DECARBONIZATION OF PRIMARY ALUMINUM PRODUCTION**



## Refining

The first step in producing primary aluminum is refining: retrieving alumina from bauxite ore. Refining requires two high-temperature processes that currently use fossil fuel energy. Alumina refining accounts for 16 percent of GHG emissions from aluminum production due to its use of fossil fuels to produce heat (Figure 4a). The reliance on fossil fuel energy for this heat also contributes to air pollution. As part of refining, the bauxite ore first undergoes the Bayer process, where caustic soda and steam are added to precipitate out aluminum hydroxide.[12] The Bayer process is done at different temperatures depending on the composition of the ore.[13] The low-temperature Bayer process occurs at 175 to 230 degrees Celsius at pressures of 600 to 800 kilopascals (kPa), and the high-temperature Bayer process occurs at 325 to 400 degrees Celsius at pressures of 5,000 to 10,000 kPa.[14] The aluminum hydroxide is then decomposed at 1,000 degrees Celsius in a step called calcination, which forms alumina and releases water as a byproduct.[15]

### Bayer Process

For the low-temperature Bayer process, one promising decarbonization solution is using cleanly powered mechanical vapor recompression (MVR).[16] MVR is a process that uses a series of compressors to increase the temperature and pressure of waste steam. MVR is extremely efficient (requires one-third of the power of an electric boiler) and can therefore be powered cleanly.[17] To ensure a steady supply of clean electricity to power MVR, electricity storage will likely need to be deployed in conjunction.[18] MVR is not yet proven at commercial scale. Global alumina and aluminum producer Alcoa is working on a first-of-its-kind pilot demonstration of MVR at a refinery in Australia.[19] MVR is expected to be ready for commercial-scale refining around 2030.[20]

For the high-temperature Bayer process, electric boilers powered by clean electricity for steam production are a promising option, as MVR cannot get to the necessary high temperatures.[21] However, MVR can be combined with electric boilers to increase efficiency in a process called double digestion.[22] Additionally, thermal storage can support the economics of electric calcination by reducing refineries' reliance on the grid during times of peak pricing by providing a stable supply of previously generated, stored heat.[23] Thermal batteries are currently in development and show promising signs of commercializing soon.[24] Electric boilers are a mature technology, but they have not been proven at scale for the high pressure of the high-temperature Bayer process.[25] There are demonstrations of electric boilers for this application in Ireland and Brazil operated by alumina and aluminum producers Rusal and Norsk Hydro, respectively.[26] Electric boilers for the high temperature Bayer process are expected to be ready for full-scale commercial operation by 2030.[27]

### Calcination

For calcination, which currently combusts fossil fuels for heat, two decarbonization levers exist. One is electric calcination, which uses electricity to produce the required heat.[28] Alcoa has also started a first-of-its-kind demonstration of electric calcination at a separate refinery in Australia.[29] Electric calcination is expected to be commercially viable by 2035, but it may be difficult to retrofit into existing refineries due to the high costs and technical constraints associated with upgrading electricity supply infrastructure.[30]

The second decarbonization lever is green hydrogen calcination, which combusts green (electrolytic powered by renewable electricity) hydrogen to produce heat.[31] This may be easier to retrofit within existing refineries, but it is less efficient and creates more on-site air pollution than electric calcination and would require the build-out of green hydrogen infrastructure. Rio Tinto started a techno-economic feasibility study for green hydrogen calcination in 2021.[32] Green hydrogen calcination is expected to be commercially viable after 2035.[33] Both electric and green hydrogen calcination will produce pure steam that is not contaminated with fossil fuel combustion byproducts, so this steam can be fed into an MVR system for additional water and energy savings from alumina refining.[34]

## Smelting

The next step in aluminum production is smelting: turning alumina into aluminum. This process is extremely energy intensive and very carbon intensive. Smelting accounts for 76 percent of GHG emissions from global aluminum production, mainly due to its use of electricity (Figure 4a). The Hall-Héroult smelting process is the most widely used method. In the Hall-Héroult process, smelting occurs in a large box called an electrolytic cell or pot. The cell is filled with a salt called cryolite; large cylinders of carbon called carbon anodes are inserted into the cell.[35] Carbon anodes are produced outside of the smelting pot by baking petroleum coke and pitch tar at 1,120 degrees Celsius.[36] Alumina is then fed into the pot. A large electric current runs through the cell and generates enough resistance to heat the pot's contents to 1,000 degrees Celsius and melts the cryolite and the alumina.[37] The electricity used in the process leads to indirect $CO_2$ emissions when it comes from fossil fuel power plants.

The electric current also facilitates a chemical reaction by breaking the aluminum-oxygen bonds in alumina. The pure aluminum pools at the bottom of the pot, and the oxygen reacts with the carbon anodes to form $CO_2$. These $CO_2$ emissions are called process emissions because they result from the chemistry of the reaction, rather than from fossil fuel combustion. In addition to $CO_2$, smelting can form perfluorocarbon (PFC) process emissions due to fluorine in the cryolite reacting with the carbon anodes. **These PFCs are GHGs that are thousands of times more potent per molecule than $CO_2$ and last for tens of thousands of years longer in the atmosphere.**[38]

This section will discuss options for reducing emissions from aluminum smelting, both emissions from electricity used during smelting and $CO_2$ and PFC process emissions.

### Emissions from Electricity

Smelting is very electricity intensive. It takes over 14,000 kilowatt-hours (kWh) of electricity to produce one metric ton of aluminum.[39] The average U.S. primary aluminum smelter draws 280 megawatts (MW) of power 24-7, 365—as much as a city of 550,000 people (Table S3).[40] Since smelters generally run continuously, they need firm power, and most smelters around the world use fossil fuel electricity (which can be generated continuously), rather than electricity from intermittent renewables.[41] As a result, GHG emissions from electricity generation account for over half of the emissions from primary aluminum production. Reliance on fossil fuel electricity also releases air pollutants that are harmful to human health.

To reduce or eliminate emissions related to the electricity necessary for aluminum smelting, facilities can switch from electricity generated from fossil fuels to decarbonized sources of electricity. To facilitate this electricity transition, smelters can also implement electricity demand flexibility measures to maximize use of relatively inexpensive but intermittent sources of clean electricity, such as wind and solar.

#### *Electricity generation*

For electricity-related emissions, electricity decarbonization is the primary decarbonization lever. One option is to connect aluminum smelters with clean, firm power. Currently, the small number of smelters that run on clean electricity are using hydropower, like at Alcoa's Massena smelter in New York and at Canadian smelters, or geothermal, like at Icelandic smelters.[42] While firm and low in GHG emissions, geothermal power plants face limited deployment and traditional hydropower faces high costs due to geography constraints.[43] Traditional hydropower projects also cause irreversible environmental damage.

Although the levelized cost of electricity (LCOE) of intermittent renewables has historically been higher than that of fossil fuel electricity, there have been large decreases in the LCOE of utility-scale solar and wind power over the last two decades.[44] These intermittent renewables are now cost competitive with fossil-fuel-based electricity sources.[45] Newer and firmer sources of clean electricity, such as enhanced geothermal and concentrating solar power may become more widespread in the future, but they are still less mature and more expensive than intermittent sources of clean electricity.[46]

Given that the LCOE of intermittent renewables has decreased at a faster rate than that of other clean power sources, and the deployment of intermittent renewables has increased at a faster rate than other clean power sources, future electricity decarbonization for smelting may rely on these intermittent renewables.[47] Aluminum producers such as Hindalco and Alcoa are investing in wind and solar power to provide some or all of their smelters' baseload power consumption in countries like India, Spain, and Australia.[48] Alcoa and renewable energy developer Greenalia entered into a long-term power purchase agreement for renewable energy to provide up to 183 MW of the San Ciprián aluminum smelter's baseload power (about 45 percent of the energy needed to meet the smelter's maximum aluminum production capacity).[49] In Australia, Alcoa's Portland smelter, which already sources more than 30 percent of its electricity from renewables, plans to get to 100 percent renewable electricity usage through a planned 1,000 MW offshore wind farm project.[50]

### *Electricity demand flexibility*

Given the rapid deployment of cheaper intermittent renewables, technologies that enable electricity demand flexibility can help smelters optimize clean power usage when it is available and reduce the need for firm power. This can be achieved by two main (and complementary) strategies: first, by modulating production to coincide with times of greater energy generation and, second, by effectively storing clean energy to use at times of lower energy generation.

Conventional smelting cells need to run continuously because cooling and reheating the whole cell requires more than two days and can damage cell components.[51] New smelter designs, such as the commercial-scale-demonstrated and retrofittable EnPot technology (currently installed and operating at one smelter), can instantly modulate smelter power consumption by as much as 20 percent.[52] This modulation would allow a smelter to increase production during times of excess renewable supply and decrease production during renewable scarcity.

Additionally, the development of large-scale and long-duration on-site electricity storage for smelters could also achieve this modulation effect from a grid demand perspective. Multiday energy storage technologies (e.g., hybrid flow batteries, metal anode batteries) are being developed, and some are at a technology readiness level (TRL) of nine, which means the technology has been proven.[53] Aluminum smelters can be paired with long-duration energy storage projects that can help modulate smelter demand for clean grid electricity—i.e., smelters can store electricity during times of excess renewable generation and use on-site stored electricity during times of renewable scarcity. In fact, with advanced modulation and energy storage technologies, aluminum smelters can become an asset (rather than burden) for electrical grids that may become more reliant on intermittent renewable sources by storing or using excess electricity when available and reducing their usage of grid electricity when unavailable.

## Process Emissions

Besides the electricity-related emissions, smelting also generates process emissions in the form of $CO_2$ and PFCs. These process emissions account for about 15 percent of total emissions from primary aluminum production (Figure 4a). This section will examine options for eliminating either PFC emissions or $CO_2$ emissions before turning to advanced process changes that have the potential to eliminate *both* PFC and $CO_2$ process emissions.

### *PFC emissions reduction*

Technologies that can consistently and automatically control alumina levels in the smelting pot can reduce the occurrence of anode effects and therefore PFC emissions. Anode effects occur when alumina levels drop below a certain point. The aluminum production reaction stops, and fluorine atoms in the molten salt start to react with the carbon anodes.[54] Alumina concentration can be determined by measuring the electrical resistance inside the pot.[55] Therefore, the first step to reducing PFC emissions is installing modern computer-controlled systems that can accurately measure pot resistance. First introduced in the 1960s, computer systems today can complete 10 to 100 resistance readings per second.[56] Point feeders were also introduced in the 1960s and were quickly integrated with these computer systems.[57] In point feeder systems, alumina is added in small amounts at multiple points in the center of the pot to prevent sludge formation, which decreases cell efficiency, and to prevent low alumina levels, which cause anode effects.[58] Combining computer monitoring and point feeders allows for automated computer control of alumina concentrations in smelter pots. These control technologies are mature and widely used, but smelters in countries such as the United States and China still rely on outdated and manual controls to prevent anode effects.[59] As a result, they have much higher levels of PFC emissions. Chinese and U.S. smelters on average emit at least 40 times as much PFCs as the best available technology emits, but this could be abated with readily available equipment and technology updates (Table S4).[60]

### *$CO_2$ emissions reduction*

To address $CO_2$ process emissions alone, some form of carbon capture would need to be deployed. However, the low concentration of $CO_2$ (1 percent) in the mixture of gases released from smelters would make carbon capture very expensive; the scrubbing required to remove the contaminants would also add costs.[61] Additionally, smelters would potentially need to be redesigned to allow for easier separation of $CO_2$, or more novel carbon capture methods would need to be deployed.[62] The DOE estimates carbon capture on Hall-Héroult electrolysis would cost $140 to $290 per ton of $CO_2$ abated after incentives from the Inflation Reduction Act (IRA) are considered.[63] For comparison, carbon capture on cement production, which emits higher concentrations of $CO_2$, would cost $35 to $65 per ton of $CO_2$ abated after IRA incentives.[64] Norwegian aluminum producer Norsk Hydro is developing some carbon capture technologies for smelters and aims to have a pilot carbon capture facility by 2030.[65] Although there is some industry interest in carbon capture on Hall-Héroult electrolysis, given the very low concentration of $CO_2$ released from smelters and the resulting high costs of abatement, carbon capture alone will likely be neither an optimal technological solution nor an economic decarbonization lever to address smelting $CO_2$ process emissions.

### *Advanced process changes*

**To address both PFC and $CO_2$ process emissions, the Hall-Héroult smelting process needs to be fundamentally changed or replaced.** Here we describe three methods that have the theoretical potential to replace the Hall-Héroult smelting process: use of inert anodes, carbothermic reduction, and the aluminum chloride process.

The first method would be the use of inert anodes instead of carbon anodes. Inert anodes are not consumed in a reaction. They would facilitate the same electrochemical reaction of alumina to aluminum through the loss of oxygen, but this oxygen would not react with any carbon anode. Thus, only oxygen would be emitted. However, using inert anodes requires a redesign of the smelting pot system to increase efficiency to offset the increased energy requirement of inert anodes compared to carbon anodes.[66] Choosing the correct materials for inert anodes is also challenging due to the harsh operating conditions of smelters.[67] In 2018, aluminum giants Alcoa and Rio Tinto entered into a joint venture partnership alongside Apple and the Canadian and Quebecois governments called Elysis to develop inert anodes.[68] In June 2024, Rio Tinto announced that it will build a new demonstration plant with ten carbon-free smelting pots using technology licensed by the Elysis joint venture.[69] Production capacity of the plant will be 2,500 tons per year, and production is targeted to start by 2027.[70] The success or failure of this plant will provide critical information as to whether inert anode technology can eventually scale to a commercial level.

A second alternative to electrochemical aluminum production is carbothermic reduction. In this reaction, alumina is heated to 2,000 degrees Celsius with carbon to form aluminum and carbon dioxide.[71] Although millions of dollars and decades of research have been invested in this technology, the operation of a pilot-scale facility demonstrated numerous challenges inherent to this technology that inhibit its commercial viability.[72] Parasitic reactions decrease the reaction efficiency of carbothermic reduction, high levels of CO and $CO_2$ are still emitted, and the energy requirement is too high.[73] Alcoa operated a large pilot carbothermic reduction plant in the early 2000s with Elkem, but the plant shut down after a few years.[74]

The final alternative to the Hall-Héroult process is another electrochemical process that uses a different chemistry: the aluminum chloride process. First, alumina reacts with carbon and chlorine to produce aluminum chloride and carbon dioxide in a reaction called carbochlorination.[75] The aluminum chloride is then electrochemically reduced into aluminum metal and chlorine gas in a similar reaction to the Hall-Héroult process.[76] The aluminum chloride process has some advantages to the Hall-Héroult process: electrolysis occurs at a lower temperature (720 degrees Celsius), the overall energy consumption is lower, and the $CO_2$ concentration from the carbochlorination process is quite high, so $CO_2$ can be more easily captured.[77] Additionally, while bauxite can be used as a feedstock to produce alumina, the production of alumina can be bypassed entirely in a process called direct chlorination.[78] Direct chlorination of various, non-bauxite minerals (e.g., anorthosite, kaolinite) could yield aluminum chloride, so the Bayer process could be avoided, and the feedstock for alumina could be diversified in the future.[79]

An estimated $100 million was invested into research and development for the aluminum chloride process from the 1960s to the 1980s.[80] Alcoa operated the largest plant, a demonstration-scale facility in Texas, from 1976 to 1985.[81] The main challenges with the aluminum chloride process were producing aluminum chloride of an acceptable purity and addressing the formation of toxic chlorine gas.[82] Starting in 2016, Norsk Hydro has been involved in developing a new kind of aluminum chloride process.[83] Called HalZero, this process carbochlorinates alumina using carbon monoxide as the carbon source and chlorine gas. The $CO_2$ byproduct is separated into oxygen (which is emitted) and carbon monoxide, which is recycled back into the carbochlorination process. The chlorine gas produced during the aluminum chloride electrolysis is also recycled. Norsk Hydro expects a test facility to be operating by 2025 and pilot-scale production by 2030.[84] A rapid, industry-wide transition away from the traditional Hall-Héroult process for aluminum production seems unlikely, but the successful commercialization of the aluminum chloride process would provide another solution to eliminating PFCs and process emissions.

## INERT ANODES FACE SCALE-UP TEST

There has been renewed interest in inert anodes as a decarbonization solution for process emissions from smelting due to recent strides toward commercialization of the technology. The first inert anode patent was one of multiple patents filed by Charles M. Hall (of Hall-Héroult) in 1889.[85] Research continued on inert anodes, including well-funded efforts by Alcoa, through the 1980s and 1990s.[86] The formation of the joint venture Elysis in 2018 between aluminum giants Alcoa and Rio Tinto—along with the Canadian and Quebecois governments—to commercialize a zero-carbon smelting process reignited investment in inert anode development.[87] This section will discuss how inert anode technology works and its future development outlook.

Inert anodes can address the almost 20 percent of process emissions from aluminum production that cannot be efficiently abated through other means.[88] These process emissions occur during smelting from the carbon anodes that are inserted into the electrochemical smelting pot. An electric current runs through the cell and causes the carbon anode to react with the oxygen in alumina ($Al_2O_3$) to form $CO_2$. The carbon loses some electrons in this process, and these electrons are subsequently gained by the aluminum ions in alumina to form molten aluminum metal, which pools at the bottom of the electrochemical cell and functions as the cathode.

An inert anode would allow for electron transfer to occur without directly participating in the reaction. Therefore, only oxygen would be produced, rather than $CO_2$. However, inert anodes alone are not a comprehensive solution to the aluminum emissions problem. Without changes to the physical structure of the smelter (discussed below), inert anodes have a higher energy requirement compared to carbon anodes.[89] ($CO_2$ formation releases energy, whereas oxygen formation does not, so this leads to a higher theoretical energy requirement when producing oxygen with inert anodes than when producing $CO_2$ with carbon anodes.[90]) Directly swapping carbon anodes with inert anodes would therefore lead to even higher electricity consumption during smelting. If this electricity is not clean, the additional emissions from electricity production could offset reductions from the elimination of process emissions.

Decreasing the distance between the anode and cathode (anode-cathode distance, or ACD) reduces the voltage required to run the current through the electrochemical cell by lowering internal cell resistance.[91] Traditional Hall-Héroult smelting pots keep a larger than optimal ACD to prevent molten aluminum waves from touching the carbon anode and short-circuiting the cell.[92] Therefore, decreasing the ACD can yield energy savings that can be combined with inert anodes to eliminate process emissions without potentially increasing emissions from dirty electricity.

To decrease the ACD, the smelting cell must allow for drainage of the molten aluminum as it forms so that electromagnetically induced waves in the molten aluminum do not pose a short-circuiting risk. In other words, only a thin layer of molten aluminum should function as the cathode, not the full pool, so that the anode can get closer to the molten aluminum surface. Aluminum drainage is allowed by introducing a vertical component of the pot (sloping pot walls) or by creating a completely vertical cathode altogether.[93] In either case, a surface or material that is wettable (nonreactive) by aluminum is necessary for the cathode. Current Hall-Héroult cells do not have pot linings wettable by aluminum, so a thin electrolyte layer exists between the molten aluminum pad and the pot lining (Figure 6).[94] If the pot lining slants downward, the electrolyte layer would simply pool at the bottom of the cell, and unwanted reactions between the aluminum and pot lining would occur. Therefore, aluminum-wettable materials for cathodes must also be developed to allow for ACD reduction and ultimately efficient usage of inert anodes.

**FIGURE 6: SCHEMATIC SHOWING TRADITIONAL HALL-HÉROULT CELL CROSS SECTION OF ANODE, ACD, ELECTROLYTE, AND METAL CATHODE (ALUMINUM)**

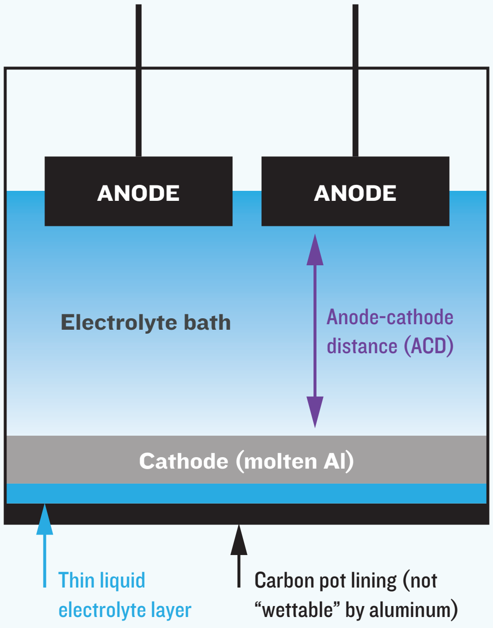
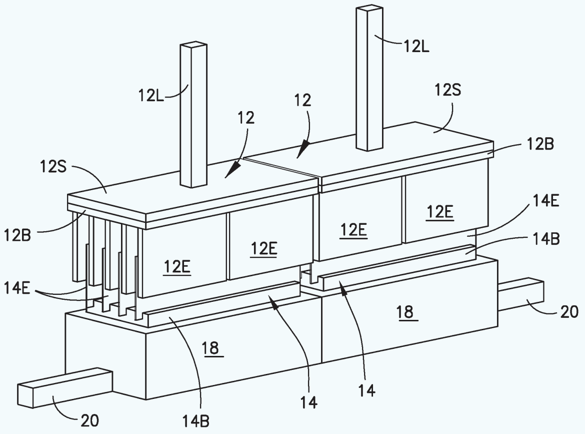


**FIGURE 7: SCHEMATIC FROM ALCOA PATENT SHOWING REPEATING UNITS OF VERTICAL WETTABLE CATHODES MOUNTED TO THE BOTTOM OF A SMELTING POT AND REPEATING UNITS OF INERT ANODES ATTACHED TO A MOVABLE ARM**



*Source:* Xinghua Liu, "Electrode Configurations for Electrolytic Cells and Related Methods," patent no. WO/2017/165838, filed March 24, 2017, issued September 28, 2017, World Intellectual Property Organization, https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2017165838.

A vertical electrode cell is one way to combine inert anodes with vertically oriented cathodes made of an aluminum-wettable material. In 2017, Alcoa received a patent detailing configurations for vertical electrode cells.[95] Repeating units of wettable cathodes are mounted to the bottom of the cell, and repeating units of inert anodes are attached to an arm that can move up, down, and side to side to control ACD and anode-cathode overlap (to adjust cell resistance and maintain stable cell temperature) (Figure 7).

After the formation of Elysis in 2018, commercial-grade aluminum has been produced using an inert anode method. Elysis-produced aluminum has been used in products such as Apple's iPhone SE, wheels for Audi's e-tron GT, and cable components for Nexan.[96] In 2022, Elysis announced that they were starting construction on a commercial-scale anode and cathode manufacturing facility.[97]

In June 2024, Rio Tinto and the Quebecois government announced a new joint venture to build a demonstration plant using technology licensed by Elysis.[98] The plant's expected capacity is 2,500 metric tons of aluminum per year, and production is targeted to start in 2027.[99] Successful scale-up of inert anodes will require designing electrodes that can withstand extremely difficult operating conditions, manufacturing these electrodes at scale, and redesigning the electrochemical cell without significantly raising the cost of aluminum. If this new plant can successfully demonstrate smelting without process emissions, then the path to fully scaling up and commercializing an inert anode process will become more feasible and less risky.

## CENTURY ALUMINUM'S FORTHCOMING GREEN ALUMINUM SMELTER MUST DEMONSTRATE GREEN SMELTER OPERATIONS AND DESIGN

In March 2024, the DOE Office of Clean Energy Demonstrations' Industrial Demonstrations Program (OCED IDP) selected Century Aluminum's proposed "green aluminum smelter" for project funding, pending award negotiations.[i] If completed, this would be the first new smelter built in the United States in 45 years. It is also expected to double capacity for primary aluminum in the United States and bring 1,000 permanent union jobs.[100] The project announcement states that it will be built in Kentucky or the Ohio and Mississippi river basins. The project also claims it will reduce GHG emissions by 75 percent compared to baseline technologies.

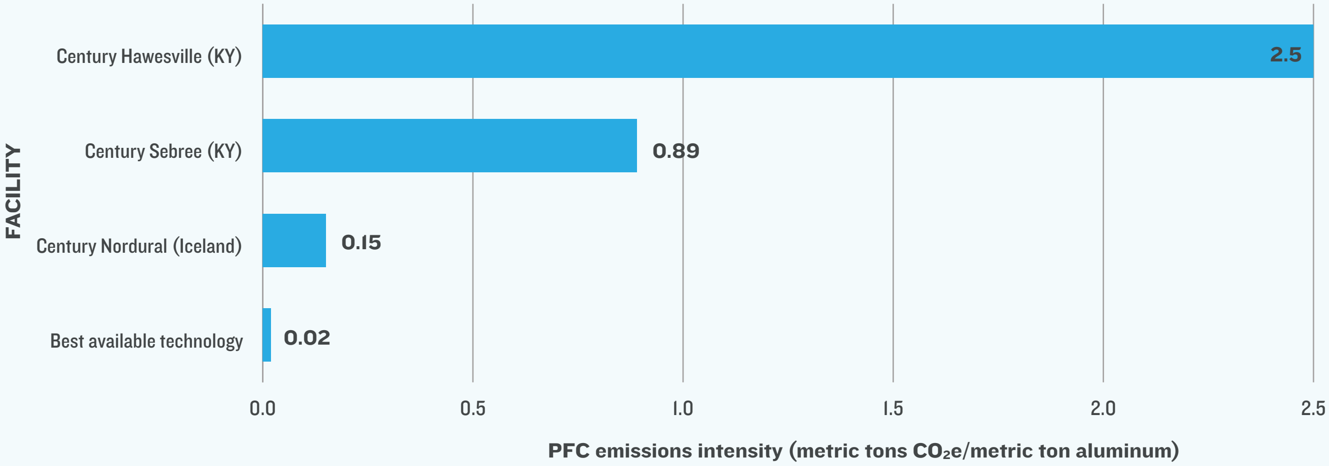
Century Aluminum's green aluminum smelter is a unique opportunity to build a state-of-the-art U.S. smelter that can catalyze the transformation of the domestic primary aluminum industry to be clean and climate friendly. To achieve truly green aluminum production, four criteria should be met as Century designs its new smelter:

- usage of clean electricity
- maximal reduction of PFC emissions
- implementation of advanced toxic pollution mitigation strategies and technologies[ii]
- exploration of novel pathways to continue reducing GHG emissions

**CLEAN ELECTRICITY USAGE:** Because aluminum smelters require an immense amount of electricity 24-7, ensuring that only truly clean electricity is used is critical. To the maximum extent possible, not only should a clean smelter run on clean electricity, but its operations should support overall grid decarbonization. Supporting grid decarbonization includes measures such as incentivizing build-out of renewable electricity sources for the grid and implementing on-site energy storage or production modulation technologies to balance supply and demand of clean electricity.

**FIGURE 8: PFC EMISSIONS COMPARISON AT CENTURY ALUMINUM FACILITIES, 2021**

Century Aluminum's U.S. facilities had much higher PFC emissions intensities than Century's Nordural facility.



*Source:* Phil McKenna, "Why American Aluminum Plants Emit Far More Climate Pollution than Some of Their Counterparts Abroad," *Inside Climate News*, December 6, 2022, https://insideclimatenews.org/news/06122022/why-american-aluminum-plants-emit-far-more-climate-pollution-than-some-of-their-counterparts-abroad/.

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[i] Publication was written with information available in August 2024 regarding Century Aluminum's green aluminum smelter.

[ii] Century Aluminum has violated air pollution and wastewater discharge pollution limits at its Kentucky smelters dozens of times in the last few years. Sierra Club, Kentucky Chapter, "Aluminum - Exposure to Toxic Pollution," accessed June 13, 2024, https://www.sierraclub.org/kentucky/aluminum.

**PFC EMISSIONS REDUCTION:** PFCs are thousands of times more potent and lasting GHGs per molecule than CO2. Although there are not yet commercialized methods to completely eliminate PFCs, U.S. aluminum smelters could dramatically reduce their PFC emissions using currently available technologies. In 2021, Century Aluminum's two Kentucky-based smelters produced 2.50 and 0.89 metric tons of CO2 equivalent of PFCs per metric ton of aluminum (Figure 8).[101] This is far higher than levels produced at Century Aluminum's Icelandic Nordural facility, which only emitted 0.15 metric tons of $CO_2$ equivalent of PFCs per metric ton of aluminum.[102]

PFC emissions can be further reduced. The current best available technology allows for just 0.02 metric tons of $CO_2$ equivalent of PFCs per metric ton of aluminum.[103] Technologies such as computer monitoring and point-feeding systems allow for greater automated control over smelting to prevent excessive PFC emissions. By implementing the best available PFC control technologies (which exist and are already deployed by Century Aluminum at other smelters), Century can produce aluminum with a PFC emissions intensity that is 98 percent lower than its current, best-performing Kentucky-based smelter.

**TOXIC POLLUTION MITIGATION STRATEGIES AND TECHNOLOGIES:** Smelting produces toxic air and water pollutants, including sulfur dioxide ($SO_2$), particulate matter, volatile organic compounds, fluoride, mercury, cyanide, lead, arsenic, and cadmium.[104] U.S. smelters have regularly violated air and water pollution limits.[105] Therefore, it is important that a new, state-of-the-art U.S. aluminum smelter invest in the best possible pollution monitoring and control technology, not only to comply with existing regulations but also to demonstrate what is maximally possible in terms of pollution reduction.

**NOVEL PATHWAYS FOR GHG REDUCTIONS:** In addition to using commercialized technologies to reduce GHG emissions and toxic pollution, a new smelter funded by OCED IDP should explore other novel pathways for emissions reductions. By demonstrating and de-risking not yet commercialized decarbonization technologies and strategies for aluminum production, a green aluminum smelter could pave the way for further development and deployment of technologies that address currently unavoidable emissions in the primary aluminum industry.

## Improved Secondary Aluminum Production Can Play a Role in Aluminum Decarbonization

Secondary aluminum is aluminum that is recycled from scrap back into a usable product. Inputs for secondary aluminum include both pre-consumer aluminum (recycled directly from scrap produced during primary aluminum production) and post-consumer aluminum scrap (recycled from finished products, such as beverage cans and cars). Globally, approximately 33 Mtpa of secondary aluminum was produced in 2019 (Figure 9).[106] Of this, 20 Mtpa was from post-consumer scrap, and 13 Mtpa was from pre-consumer scrap.[107]

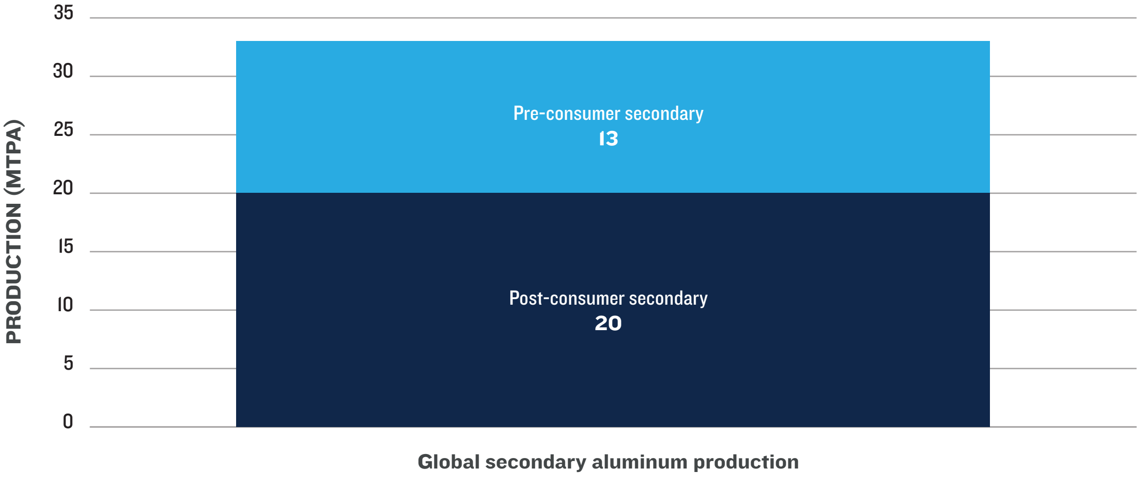
Secondary aluminum production requires just 5 percent of the energy needed for primary aluminum production, so its use can be an impactful decarbonization lever.[108] However, secondary aluminum production currently relies on primary aluminum as an input, and 40 percent of secondary aluminum globally comes from scrap directly from primary aluminum production.[109] The reliance on primary aluminum is necessary to help increase the quality of secondary aluminum. Although aluminum is an infinitely recyclable material, it is often difficult to separate and recover aluminum from contaminants, which then degrade the quality of secondary aluminum. Therefore, in addition to reducing primary aluminum's carbon intensity, maximizing secondary aluminum's circularity will increase its potential as a decarbonization lever.

Given the dramatically lower carbon and energy footprint of secondary aluminum (particularly from post-consumer scrap) compared to primary aluminum, fulfilling some future aluminum demand with secondary rather than primary aluminum could be an effective way to reduce emissions from aluminum production overall. Modeling suggests if global aluminum demand increases by 80 percent (from 2020) by 2050 and secondary aluminum production continues to grow at a similar rate, then 50 percent of demand in 2050 could be met by post-consumer secondary aluminum.[110]

However, secondary aluminum faces challenges with available quantity and quality to meet aluminum demand. Secondary aluminum can only be made from existing aluminum. Therefore, if more aluminum scrap does not become available to be made into aluminum, or aluminum is landfilled instead of recycled, then secondary aluminum cannot serve to meet additional aluminum demand. Secondary aluminum also typically

## FIGURE 9: GLOBAL SECONDARY ALUMINUM PRODUCTION BREAKDOWN, 2019

More than half of secondary aluminum came from post-consumer scrap.

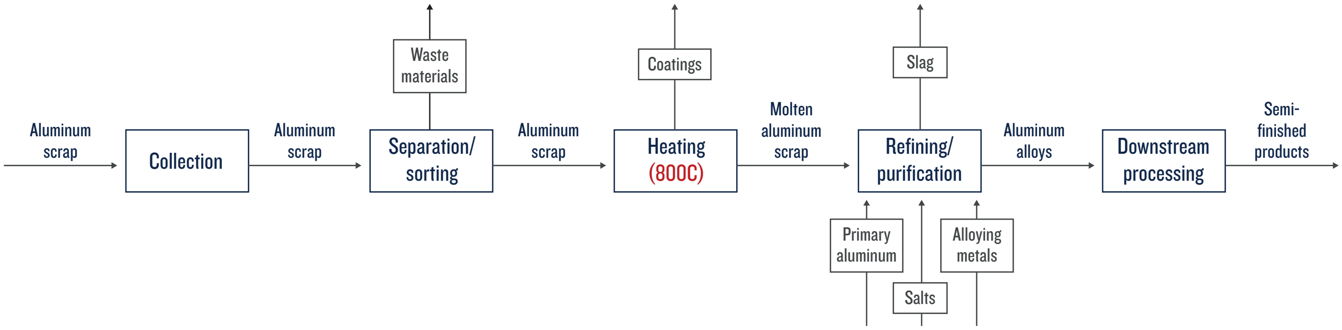


*Source:* International Aluminium Institute, "IAI Material Flow Model 2021 Update," May 2021, https://international-aluminium.org/wp-content/uploads/2021/05/IAI-Material-Flow-Model-2021-Update.pdf.

has a lower quality than primary aluminum. While pure primary aluminum can be made from bauxite ore and then combined, or alloyed, with other metals for a specific intended end use, secondary aluminum often consists of a mix of alloys that may produce undesirable characteristics in end products. As a result, under current dominant processes, secondary aluminum use can be limited by its purity, even though theoretically it could be used in the same applications as primary aluminum.

Process improvements can increase the quantity and quality—and therefore circularity—of secondary aluminum. These improvements also have the potential to save energy and thereby further decrease the carbon footprint of secondary aluminum. Secondary aluminum production consists of a series of steps to turn pre-consumer and post-consumer scrap into aluminum (Figure 10). This section discusses each of the steps and the technologies and strategies that can improve their performance to produce secondary aluminum at higher quantities and qualities.

## FIGURE 10: BLOCK FLOW DIAGRAM ILLUSTRATING THE SECONDARY ALUMINUM PRODUCTION PROCESS



*Source:* BCS, *U.S. Energy Requirements for Aluminum Production*, Industrial Technologies Program, DOE, February 2007, 65-66, https://www.energy.gov/eere/amo/articles/us-energy-requirements-aluminum-production; Sai Krishna Padamata, Andrey Yasinskiy, and Peter Polyakov, "A Review of Secondary Aluminum Production and Its Byproducts," *JOM* 73, no. 9 (September 1, 2021): 2604, https://doi.org/10.1007/s11837-021-04802-y.

## Collection

First, aluminum scrap is collected from consumers as well as aluminum manufacturers. Pre-consumer aluminum scrap is easily recovered because manufacturers have control over its collection. However, post-consumer aluminum scrap can be harder to collect. Aluminum used in certain applications, such as building and automotive, has a recycling rate over 90 percent.[111] However, some regions of the world have very low recycling rates of smaller-scale consumer goods like aluminum cans and packaging.[112] In the United States, only 45 percent of used beverage cans are recycled due to factors such as lack of collection infrastructure, consumer behavior, and the high cost of recycling facilities (cities will landfill aluminum rather than send it to a recycling facility).[113] Measures such as improved and expanded recycling infrastructure and monetary incentives for recycling may help improve collection rates, and thus increase the amount of secondary aluminum that can be produced.

## Separation or Sorting

After collection, aluminum is sorted. This includes separating aluminum-containing products from other waste materials (e.g., rubber, glass, plastics) and sorting products containing different alloys or grades of aluminum.[114] When pure, primary aluminum is initially alloyed, the type and amount of the alloying elements affect the properties of the final aluminum alloy. Different aluminum alloys can have very different properties, and these properties can be incompatible if different alloys are mixed together. Therefore, effective sorting by alloy is important to prevent mixed-alloy secondary aluminum products, because these products will not be as desirable for end uses as single-alloy aluminum products would be.

More intentional sorting practices have the potential to generate higher quality secondary aluminum from the automobile recycling industry. Automobiles have the potential to yield high-quality scrap if components are separated from the vehicle before they are shredded. However, in the United States, most scrap yards (which tend to be small, cost-conscious operations) directly shred the whole automobile, which tends to yield low-quality scrap.[115] Most of this scrap is exported to Asia and Mexico, where it is manually separated, and some is landfilled.[116] In 2023, the United States produced 3.3 million tons of secondary aluminum and exported 2.1 million tons of aluminum scrap.[117] Investment in sorting technologies for facilities like scrap yards and materials-recovery facilities, which often landfill aluminum due to misidentification by older sorting technologies, can not only keep aluminum out of landfills but also retain the value of scrap for improved material circularity.

A strategy to help increase separation efficacy and circularity is closed-loop recycling. Closed-loop recycling systems recycle aluminum back into the same end use.[118] For example, secondary aluminum and rolled aluminum producer Novelis partnered with Volvo to recycle aluminum components of Volvo cars back into car components. Implementing a closed-loop recycling system that prevents contamination by scrap sourced outside of the product system and that carefully separates aluminum alloys in end-of-life scrap yields higher quality scrap—thus allowing for greater usage of secondary aluminum. In fact, Volvo reduced the carbon intensity of these components by 78 percent by substituting primary aluminum with high-quality secondary aluminum.[119]

A complementary strategy to improved sorting methods is the use of digital tracking for scrap.[120] By tracking each piece of aluminum scrap through its lifetime, scrap can be directed to the appropriate applications to retain maximal value.[121] For example, single-alloy scrap can be used in applications that require that type of alloy, rather than decreasing the value of that scrap by mixing it with other alloys and creating mixed-alloy scrap that has more limited applications.

Finally, an upstream intervention that would make better sorting easier is to design products for recyclability.[122] If products can be designed so that aluminum components can be easily separated from other materials and metals, then separation into single-alloy streams would require fewer processing steps. Currently, it is infeasible either technologically or economically to always maximize sorting of aluminum by grade or alloy, so lower quality secondary aluminum is produced as a result.

## Heating

Heating is the greatest contributor to carbon emissions from secondary aluminum production (Figure 4b). Heat is used during secondary aluminum production for two reasons. The first is to de-lacquer (or remove) coatings like paints from aluminum surfaces. The second is to melt the aluminum for the next step of refining. Heat around 800 degrees Celsius is required, but electrification for this application is not yet commercialized at those temperatures.[123] However, many electrification technologies, such as thermal batteries, are currently in development and may soon be commercially available.[124] For now, energy efficiency measures can help reduce heating emissions.

## Refining or Purification

To remove remaining metal impurities after sorting, refining methods are used.[125] In the common practice known as remelting, some primary aluminum is melted, and then secondary aluminum is added in batches. Impurities float to the top of the molten metal bath, and salts can be added to remove additional impurities in a process called fluxing. Simultaneously, alloying metals can be added to produce desired final aluminum alloys for casting, rolling, or other downstream processes.

There is ongoing research to further improve aluminum purification through the remelting and fluxing method.[126] There are also new methods being explored, but they have yet to be commercialized.[127] Improvements in refining and purification methods would improve the utility of existing and future mixed-grade scrap and better position the secondary aluminum industry to fulfill demand for higher quality alloys.

## Centralization of Secondary Production

As collection, recovery, and sorting processes improve, the growth of aluminum mini mills could drive further efficiency and optimization improvements within the secondary aluminum industry. Mini mills are small aluminum mills that take aluminum scrap to be sorted, melted, and cast or rolled into products in one place.[128] With all processes occurring in one facility, the multiple heating and cooling steps required in the typically decentralized secondary aluminum production process can be eliminated, thus resulting in energy, cost, and emissions savings. More control over each step of the process can also lead to better quality aluminum. An example of an existing mini mill is Golden Aluminum's facility in Colorado. Their mini mill takes in scrap that is then shredded, de-lacquered, melted, combined with some pure aluminum and alloying metals, cast, rolled, and finished into a semi-fabricated aluminum product.[129] Mini mills such as these can improve the efficiency and yield of secondary aluminum production.

### SECONDARY ALUMINUM DEMONSTRATION PROJECTS WILL INCREASE SCRAP USAGE AND SAVE ENERGY

The DOE's OCED IDP selected several projects that will improve the use of scrap and save energy in secondary aluminum production. Golden Aluminum's Nexcast next-generation aluminum mini mill will implement the Nexcast process, which is a combined casting and rolling process that creates wider sheets of aluminum to meet changing demands of downstream customers.[130] The mill will also recycle 15 percent more mixed-grade aluminum scrap compared to the existing casting facility. The process will also reduce natural gas consumption, thus lowering emissions. Golden Aluminum's project of demonstrating next-generation mini mill technology will hopefully catalyze investment into mini mills and accompanying technologies that increase post-consumer scrap input into secondary aluminum production.

Another OCED selectee, Constellium's low-carbon SmartMelt furnace conversion project, will add SmartMelt furnaces to the site's cast house, where aluminum is melted and mixed with alloying metals. While the project does not explicitly state whether it will improve secondary aluminum quality or yield, it will nevertheless decrease the carbon footprint of secondary aluminum production. The SmartMelt furnace saves energy and lowers emissions by using a simulation software to track furnace temperature to optimize when each step is initiated and to allow for multiple fuel types. Energy savings will also result in decreased operating expenses, and, if successfully scaled, can bolster more sustainable secondary aluminum production both domestically and abroad.

## ALUMINUM PRODUCTION HARMS HUMAN HEALTH AND CAN BE ADDRESSED PARTLY THROUGH DECARBONIZATION

Primary aluminum production can harm human health at multiple points throughout the process. Bauxite mining in Guinea, which supplies a quarter of the world's bauxite used for aluminum production, has precipitated land grabs, water scarcity, economic poverty, political destabilization, and health problems for locals.[131] Alumina refineries around the world produce mercury-containing red mud, whose extreme alkalinity pollutes water and whose dust pollutes the air; smelting produces spent pot liner, which contains toxics like cyanide; and anode production and use for smelting release $SO_2$, particulate matter, and $NO_x$.[132] Additionally, the use of fossil energy for refining and smelting releases air pollutants. Measures that decarbonize energy sources and reduce or eliminate process emissions can address some of these pollutant hazards, but not all. Proper enforcement of hazardous waste management practices can alleviate environmental health issues arising from red mud and spent pot liner.

Secondary aluminum production often relies, in part, on primary aluminum as an input, so it is not independent of these issues. However, secondary aluminum is still mostly scrap based, so it generates less pollution, hazardous waste, and human harm than primary aluminum production. The biggest waste concern with secondary aluminum production is salt slag (or salt cake) generation. Salt slag refers to the mixture of unrecovered aluminum, metal oxides, and other byproducts from the refining step where molten salt is added to recover secondary aluminum from scrap, and it can contaminate groundwater and produce toxic gases.[133] Currently, salt slag is landfilled, but Real Alloy Recycling's zero-waste advanced aluminum recycling project (selected for OCED IDP funding) seeks to build the first salt slag recycling facility in the United States to recycle material back into the aluminum process and use the rest of the waste in other industries, such as cement manufacturing. Real Alloy Recycling's project will tackle an important waste management issue for secondary aluminum production and, if successful, will lay the foundation for a more sustainable secondary aluminum industry in the United States and globally.

# Domestic Policy Levers Can Accelerate Aluminum Decarbonization by Supporting Key Objectives

Aluminum manufacturing is an energy-intensive industry that operates on thin profit margins and is particularly vulnerable to global competition.[134] To ensure the domestic aluminum industry stays competitive, policy action will be critical for rapidly reducing emissions from domestic production—and the need is significant. As already mentioned, the DOE estimates that decarbonizing U.S. aluminum could require $10 to $15 billion in capital investment through 2050.[135] Interventions will be necessary to drive innovation for aluminum emissions reduction technologies, accelerate deployment and adoption of decarbonization solutions, and ensure that U.S. investments in aluminum decarbonization are at a competitive advantage in the global market. To support aluminum decarbonization, policymakers should focus on five key objectives:

1. Facilitate clean electricity access
2. Support research, development, and demonstration (RD&D) of emerging technologies
3. Encourage widespread commercialization of emissions reduction technologies and processes
4. Implement a climate-aligned trade policy
5. Generate and promote low-carbon aluminum procurement

## Facilitate Clean Electricity Access

Smelting one ton of primary aluminum requires more than 14,000 kWh of electricity—more electricity than the average American household uses in a year.[136] Of the four primary smelters remaining in the United States, two are grid connected, one is powered by a captive coal plant, and one is powered by hydroelectricity.[137] Due to continued reliance on fossil fuels to power the grid and smelters, electricity for primary aluminum production accounts for more than half of the GHGs emitted by the domestic aluminum industry.[138] Increasing access to clean, reliable, and affordable electricity will be key to transitioning to a cleaner primary aluminum industry. Federal and state incentives should be geared toward ensuring aluminum smelters can access clean electricity. Such federal and state incentives should include support for renewable energy deployment in general (such as the 45Y Clean

Electricity Production and the 48E Clean Electricity Investment tax credits) as well as incentives and supportive regulatory frameworks for on-site clean electricity generation and storage.

## Support RD&D for Emerging Technologies

To meet aluminum demand while also reducing emissions from the industry, public and private sector investments in innovation and pilot-scale demonstrations of emerging technologies will be critical. More than 60 percent of the emissions reductions needed to decarbonize the eight large industrial sectors emphasized by the IRA will require technologies that are not yet commercialized.[139] This is particularly important for the aluminum sector because the technologies necessary to deeply decarbonize aluminum production—including those that have the potential to eliminate process emissions from primary aluminum or that allow smelters to modulate output in a way that is more compatible with intermittent renewables—are at early TRLs. To meet this need, programs that help prove out and demonstrate early TRL projects should be refunded, expanded, or established at the federal and state level.

## Encourage Widespread Commercialization of Emissions Reduction Technologies and Processes

In addition to piloting emissions reduction solutions, policy interventions should be refunded or expanded to bring emerging technologies to commercialization. Public funding for bringing pilot-scale technologies to commercial scale and commercializing the best available technology for decarbonizing aluminum will allow widespread adoption of the technologies needed to move the needle for a clean aluminum industry.

Through the IRA and the bipartisan Infrastructure Investment and Jobs Act, the federal government started this necessary work. The DOE's OCED IDP, for instance, provides needed federal investments for proving out first-of-their-kind technologies necessary to demonstrate truly low-carbon aluminum production.

Other programs such as the 48C Qualifying Advanced Energy Project tax credit can help retrofit or reequip and expand industrial facilities, including aluminum facilities, with technologies that are designed to reduce GHG emissions by at least 20 percent or to bring them substantially lower than the industry-specific carbon intensity. More incentive programs and investment tax credits like 48C for commercialization of advanced $CO_2$ and pollution reduction technologies, alongside possible production tax credits for low-carbon industrial materials, can help reduce GHGs related to aluminum production. These programs, however, had capped funding, so they essentially amounted to a one-time investment, and aluminum decarbonization will require sustained and durable market signals.

Ultra-low-$CO_2$ aluminum is also expected to cost more due to significant investments in the commercialization of novel decarbonization technologies, thus making clean aluminum less cost competitive with traditionally manufactured aluminum. Mechanisms like a clean aluminum production tax credit or contracts for difference—which have been used to support renewable electricity growth and are being considered to support cement and steel decarbonization—can address this price gap until cost parity is reached with incumbent technologies.[140] Contracts for difference are agreements where one party, such as the government, pays the difference between the predetermined price of a product under development and the market price of that product, thereby offsetting technology investment costs and guaranteeing greater demand and price certainty.[141]

## Implement a Climate-Aligned Trade Policy

Aluminum is a trade-exposed good, meaning that it is heavily traded on global markets. This creates the opportunity for carbon leakage, or the phenomenon where GHG emissions increase in one country because corporations move production to a country that has less stringent climate-mitigation policies. The United States is already reliant on aluminum imports; the net import reliance of aluminum as a percentage of apparent consumption was 52 percent in 2022 and 44 percent in 2023.[142] Therefore, attempted decarbonization of the domestic aluminum industry could lead to carbon leakage and further shrinkage of the domestic industry. Climate-aligned trade policy can both ensure that domestic climate action is safeguarded and create a "race to the top" for emissions reductions in the global aluminum market. Bilateral or multilateral sustainable production and trade agreements, such as the Global Arrangement on Sustainable Steel and Aluminum (GASSA), can be used to tie market access of goods to their emissions intensities. Such agreements would impose tariffs or other import barriers on economies contributing to an oversupply of aluminum or production of aluminum that exceeds certain emissions thresholds.[143] GASSA conversations have currently stalled due to differences in domestic priorities between the United States and European Union.[144]

A carbon border adjustment mechanism (CBAM) is another tool that can be used to leverage the United States' manufacturing carbon advantage. A CBAM would impose a fee on imported products commensurate with the GHGs emitted during production in the country of origin.[145] A CBAM would also raise revenue that could be used to further domestic aluminum decarbonization and for technical assistance to less developed countries, among other measures.[146] Multiple countries including Australia, Canada, Japan, Norway, South Korea, and the United Kingdom are exploring carbon border fees, and the European Union CBAM went into effect in October 2023. Creating a climate-aligned CBAM would not only level the playing field by ensuring cleaner aluminum manufacturers in the United States are not at a competitive disadvantage, but it would also raise the bar internationally for cleaner aluminum production and trade.

### Generate and Promote Low-Carbon Aluminum Procurement

Encouraging public and private purchase of clean aluminum through low-carbon aluminum procurement policies will ensure that there is a market for lower-emission primary and secondary aluminum. Federal Buy Clean policies, first initiated in December 2021 through a Biden administration executive order, harness the government's large purchasing power by promoting the purchase of materials with lower embodied emissions (the GHG emissions associated with a material's life from extraction to production). Such policies create demand for cleaner materials by ensuring there is an offtake agreement through public infrastructure projects. This creates certainty for producers that can then unlock further investments in clean manufacturing. The IRA provided funding for Buy Clean programs at federal agencies including the General Services Administration, the Department of Transportation, and the Department of Housing and Urban Development. Governments should explore adding aluminum to such programs.

Demand-pull policies such as advanced market commitments (AMCs) can also play a role in incentivizing investment in industrial decarbonization and low-carbon technology RD&D. AMCs are binding contracts between a government or the private sector and a corporation that guarantees initial market demand for a developing technology at a certain price and performance standard.[147] Manufacturers are provided assurance that they will have not only an initial market for their not yet commercially available low-carbon technologies but also early access to a growing market for their products. With these guarantees in place, private industry becomes more willing to invest in RD&D for truly transformative technologies. The First Movers Coalition is an example of using AMCs for industrial materials and includes commitments for low-carbon aluminum procurement.[148] Governments should look for opportunities to encourage and support private sector procurement of low-carbon aluminum. Such procurement policies also help with emissions reporting and standard setting for low-carbon products.

## Conclusion

Aluminum is a carbon-intensive material that is necessary for the clean energy transition. As more sectors electrify and renewable electricity generation grows, more aluminum will be needed to build electric vehicles, expand the grid, and generate electricity from solar and wind. To maximize aluminum's climate benefit, primary aluminum production must be decarbonized by addressing heating, electricity, and process emissions. At the same time, secondary aluminum's circularity must be improved through landfill diversion and better sorting and refining techniques. Given the large amount of investment needed to implement these decarbonization solutions, favorable economic and trade policies must play a role in encouraging the industry's decarbonization. While the path toward aluminum decarbonization is not easy, the most promising levers are apparent. The industry can—and must—be decarbonized.

# Appendix: Supplementary Information

| TABLE S1: DATA USED TO CALCULATE 2050 DEMAND PROJECTION INCREASES | | | |
|---|---|---|---|
| | | **Notes** | **Source** |
| **2020 demand** | 86.2 million metric tons | | CRU Consulting |
| **Low 2050 demand projection** | 80 percent increase from 2020 | | Mission Possible Partnership |
| **High 2050 demand projection** | 335 million metric tons | Multiple 2050 demand projections are shown in this report, and 335 Mt was the highest forecast demand. | CM Group |

| TABLE S2: DATA USED TO CALCULATE 2021 GLOBAL ALUMINUM CARBON INTENSITY | | |
|---|---|---|
| | | **Source** |
| **2021 global aluminum production (thousand metric tons)** | 67,500 | Adam M. Merrill |
| **2021 global aluminum emissions (Mt $CO_2$)** | 1,100 | Scott et al. |

| TABLE S3A: INFORMATION USED TO CALCULATE AVERAGE U.S. SMELTER POWER USAGE | |
|---|---|
| **Information provided** | **Source** |
| Four remaining U.S. primary smelters (Century Sebree, Century Mt. Holly, Alcoa Massena, Alcoa Warrick) | Andy Home; Maria Gallucci |
| Average daily electricity consumption is 12 kWh/person | University of Michigan |

| TABLE S3B: DATA USED TO CALCULATE AVERAGE U.S. SMELTER POWER USAGE | | | | |
|---|---|---|---|---|
| **Smelter name** | **Production capacity (metric tons per year)** | **Power usage (MW) (production capacity * 14,000 / (24 * 365) / 1000)** | **Notes** | **Source** |
| Alcoa Massena | 130,000 | 208 | | Andy Home |
| Alcoa Warrick | 54,000 * 2 = 108,000 | 173 | Operating two out of three production lines since mid-2022; each smelting line has capacity of around 54,000 tons per year | Andy Home; Alcoa |
| Century Mt. Holly | 229,000 | 366 | | Century Aluminum |
| Century Sebree | 220,000 | 352 | | Century Aluminum |
| **Average power usage (MW)** | 280 | | | |

**TABLE S4: DATA USED TO CALCULATE AVERAGE PFC EMISSIONS FROM U.S. SMELTERS**

| Smelter name | 2021/2022 PFC emissions (metric tons of $CO_2e$) | Aluminum production capacity (metric tons per year) | PFC emissions intensity (metric tons $CO_2e$ / metric tons aluminum) (PFC emissions / production capacity) | Source |
|---|---|---|---|---|
| Alcoa Massena | 28,523 | 130,000 | 0.219 | EPA; Andy Home |
| Alcoa Warrick | 202,537 | 108,000 | 1.88 | EPA; Andy Home; Alcoa |
| Century Mt. Holly | 107,243 | 229,000 | 0.468 | EPA; Century Aluminum |
| Century Sebree | -- | -- | 0.89 | Phil McKenna |
| **Average U.S. smelter PFC emissions intensity (metric tons $CO_2e$ / metric tons aluminum)** | 0.864 | | | |
| **Average Chinese smelter PFC emissions intensity (metric tons $CO_2e$ / metric tons aluminum)** | 1.12 | | | Phil McKenna; Lili Pike |

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