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Aluminum Climate Impact

An International Benchmarking of Energy and CO_2 Intensities

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Global Efficiency Intelligence

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Executive Summary

Aluminum production accounts for around 2 percent of global carbon dioxide (CO_2) emissions. World aluminum production has more than doubled between 2000 and 2020. Much of this growth in production came from China, which accounted for 57 percent of global aluminum production in 2020. The energy use and greenhouse gas (GHG) emissions of the aluminum industry are likely to continue increasing because the increased demand for aluminum, particularly in developing countries, is outpacing the incremental decreases in energy and CO_2 emissions intensity of aluminum production that are happening under the current policy and technology regime.

International benchmarking of energy intensity and CO_2 emissions intensity can provide a comparison point against which a company or industry's performance can be measured to that of the same type of company or industry in other countries. Benchmarking can also be used for assessing the energy and emissions improvement potential that could be achieved by the implementation of energy efficiency or CO_2 reduction measures. Also, on a national level, policy makers can use benchmarking to prioritize energy saving and decarbonization options and to design policies to reduce energy and GHG emissions.

The global aluminum industry accounts for tow percent of total global co$_2$ emissions.

In this study, we conducted a benchmarking analysis for energy and energy-related CO_2 emissions intensity of the aluminum industry among the largest aluminum-producing countries. We focused on the two phases of aluminum production value chain responsible for the vast majority of energy use and associated CO_2 emissions: alumina production and the electrolysis process to produce aluminum. Because electricity makes up a large share of the energy used in primary aluminum production, the CO_2 emissions associated with aluminum production vary widely based on the fuel mix used for electricity in a given country or region.

Our results show that India, China, and Australia have the highest and Iceland, Norway, and Canada have the lowest energy-related CO_2 emissions intensities among the countries/region studied. Among several reasons, this is primarily because of the emissions factors of electricity used to produce aluminum in these countries (mainly in the electrolysis process). Figure ES1 shows the energy-related CO_2 emissions intensities for aluminum production in the countries/region studied, based on our system boundary of the alumina production and electrolysis phases.

Some key factors that could explain why the aluminum industry's energy and CO_2 emissions intensity values differ among the countries are: the fuel mix used for alumina production, the share of imported vs. domestically produced alumina, the electricity grid CO_2 emissions factor, the share and type of captive power used for aluminum production, the level of penetration of energy-efficient technologies, the aluminum product mix in each country, the age of aluminum manufacturing facilities in each country, environmental regulations, cost of energy and raw materials, and the boundary definition for the aluminum industry. These are discussed later in the report.

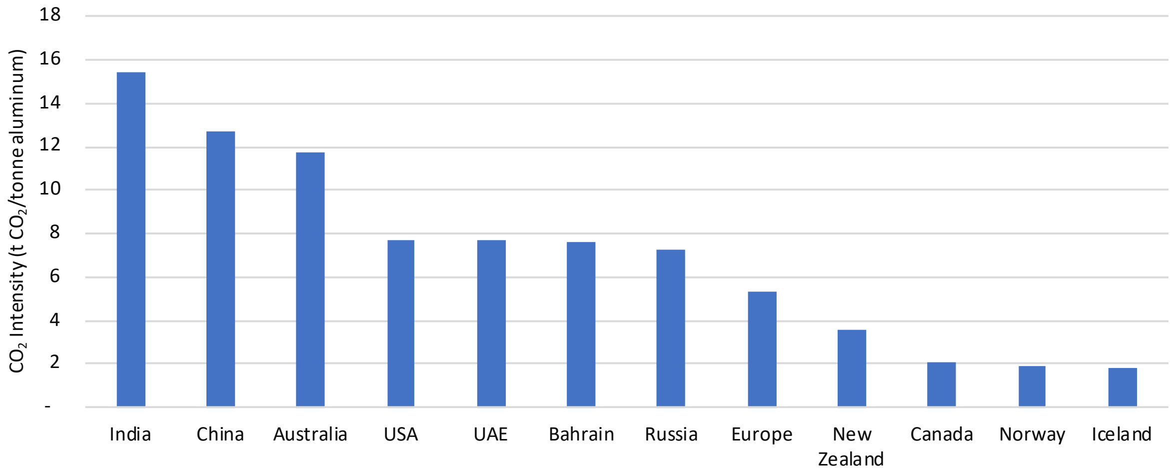

Figure ES1. The energy-related CO_2 intensity of aluminum production in the studied countries/regions in 2019
(Note: Both smelters and alumina production processes are included. The CO_2 emissions from both electricity and fuel use are included.)

In view of the projected continuing increase in absolute aluminum production and the need for deep decarbonization of the aluminum industry to meet climate targets, future reductions in absolute energy use and CO_2 emissions will require innovation beyond technologies that are widely used today. New developments will likely include different processes and power sources. Since 81% of emissions from aluminum production come from electricity, the most important measure to decarbonize the aluminum industry is decarbonization of the electricity used in aluminum production. This report sheds light on the relative performance of today's aluminum producers around the world, highlighting where these future developments can and should take place.

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1 Introduction

Primary aluminum production is one of the most energy-intensive industries worldwide. The production of alumina, an intermediate product in aluminum production, is also a highly energy-intensive process. Roughly one third of aluminum is produced from recycled scrap (referred to as secondary production) (IEA 2020a). This report focuses on primary aluminum production, which is nearly 20 times as energy intensive as processing recycled aluminum (U.S. DOE 2017).

Global aluminum demand is projected to grow at an average annual rate of 1.2%, representing over 15% growth in total demand by 2030 over current levels, as projected by the IEA (IEA 2020a). This growth in demand will be driven by continued population and GDP growth, as well as increased demand for specific aluminum-based materials, including lightweight vehicles and renewable energy technology. This significant increase in aluminum consumption and production will drive a significant increase in the industry's absolute energy use and CO_2 emissions in the absence of substantial efforts towards efficiency and decarbonization in the aluminum industry.

Aluminum is conventionally produced through the Hall-Heroult process of electrolytic reduction of alumina. Figure 1 provides a simplified schematic of the primary aluminum production process, from alumina to final products. Aluminum ore (bauxite) is first processed into alumina via the Bayer process. Alumina is then reduced to aluminum via the Hall-Héroult process. Hall-Héroult cells contain a molten cryolite electrolyte that conducts the electric current running through a carbon anode to the newly formed molten aluminum on the carbon lining (the cathode). Electrolysis through the Hall-Héroult process is by far the most energy-intensive step of primary aluminum production. The molten aluminum produced from the Hall-Heroult process is typically cast into ingots, which are transported to foundries and other processing plants to be transformed into alloys or final products. Aluminum may also be extruded into its final shape.

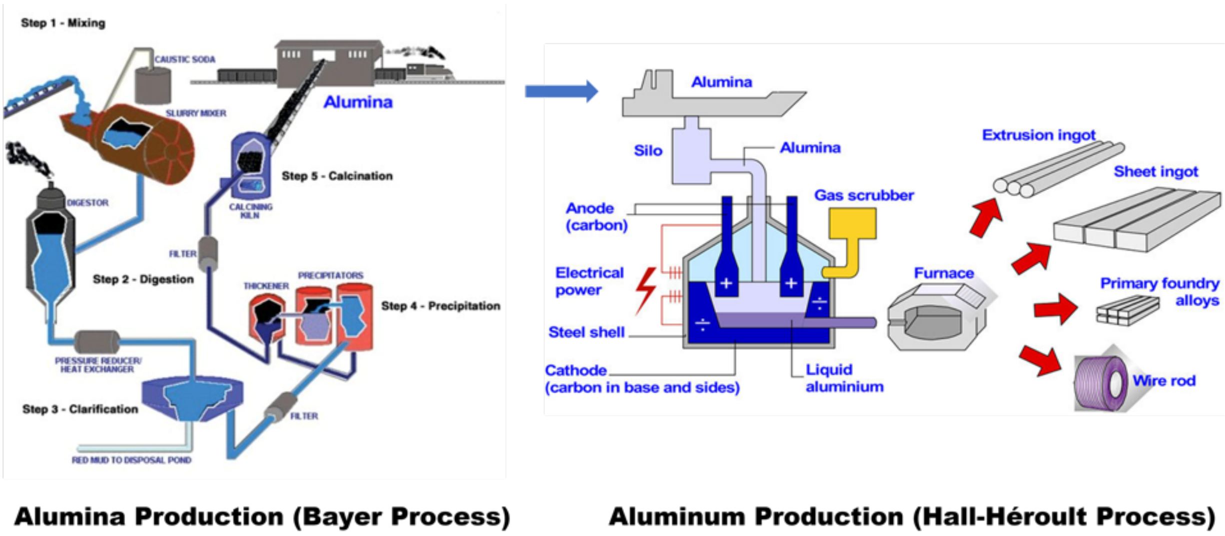


Figure 1: Primary aluminum production diagram (Image Sources: AMW 2021, Tabereaux 2010)

There are emerging technologies that aim to reduce energy use and emissions from aluminum production such as the one described in Springer and Hasanbeigi (2016). For example, new ELYSIS process developed by Alcoa and Rio Tinto replaces the carbon anodes used in traditional aluminum smelting with inert anodes eliminating the direct carbon emissions from aluminum smelter and reducing operation cost (ELYSIS 2021).

Aluminum production generates CO_2 emissions as 1) direct process emissions, in which CO_2 is the product of aluminum electrolysis, fuel used onsite mainly in alumina production, and oxidation of the carbon anode; and 2) indirect emissions from consumption of electricity used for smelting. Aluminum production also produces perfluorocarbons (PFCs), a potent greenhouse gas, when anode effects occur. Anode effects occur when the alumina ore content in the electrolytic cells falls below critical levels, and the amount of PFCs they produce depends on the frequency and duration of these events (EPA 2021). Figure 2 below shows the relative GHG emissions (based on tonnes of CO_2e) from each phase of the aluminum production supply chain.

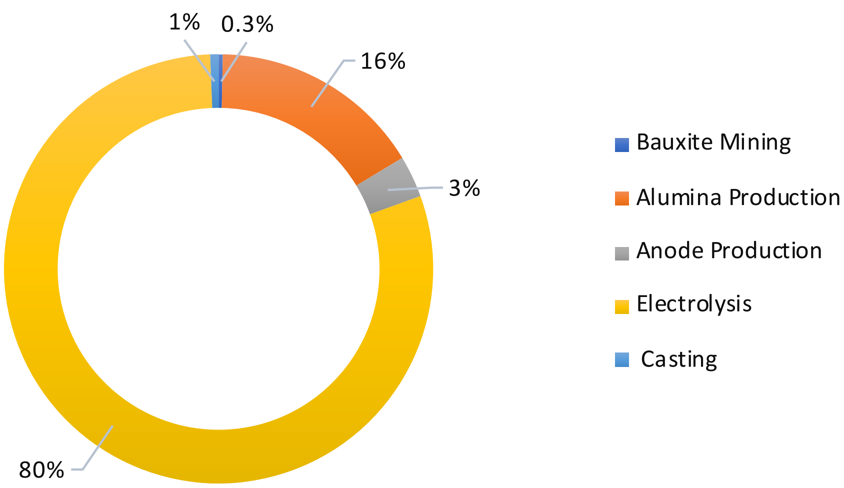


Figure 2. Share of GHG emissions by aluminum production phase – Average based on global estimates in 2019 (Source: IAI 2021a)

Alumina production and electrolysis account for 96% of GHG emissions from aluminum production. Within the electrolysis phase, emissions associated with electricity use account for 81% of GHG emissions for global average production (the vast majority of the remaining GHG emissions for the electrolysis phase come from direct process emissions of CO_2 and non-CO_2 GHGs). Therefore, for this report, we restrict the scope of our benchmarking analysis to energy use and energy-related CO_2 emissions in alumina production and electrolysis for primary aluminum production.

2 Global Aluminum Production and Trade

World aluminum production has more than doubled between 2000 and 2020 (Figure 3). In 2020, China accounted for 57 percent of global aluminum production, while its share was only 11 percent in 2000. The 2008 drop in world aluminum production was because of the global economic recession.

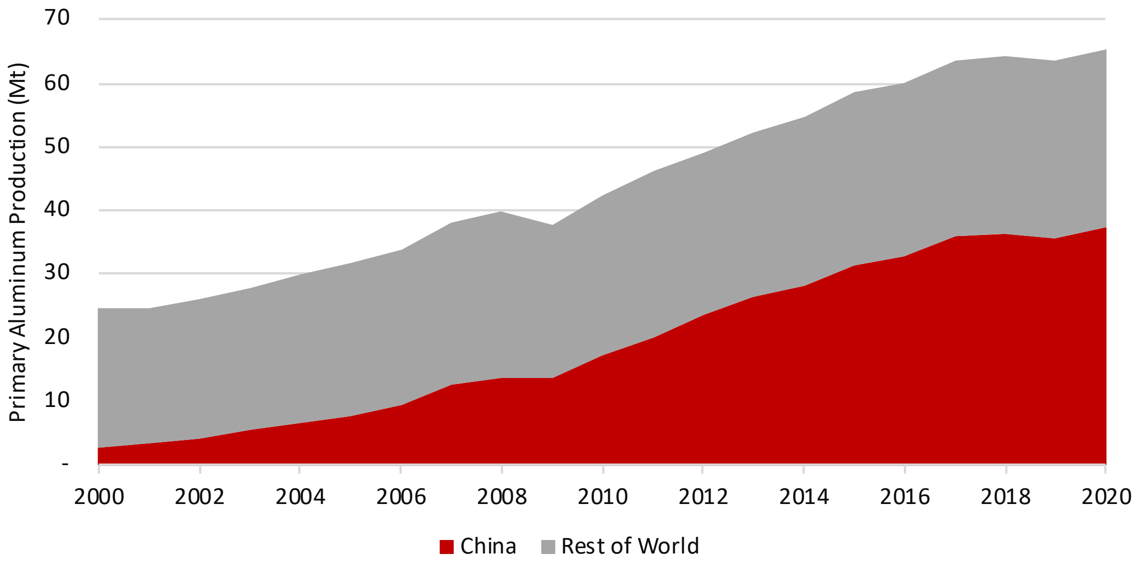


Figure 3. Primary aluminum production in China and rest of the world, 2000-2020 (IAI 2021b)

Figure 4 shows the top 10 aluminum producing countries in the world. In 2019, these top 10 producing countries accounted for 86 percent of world aluminum production (USGS 2021).

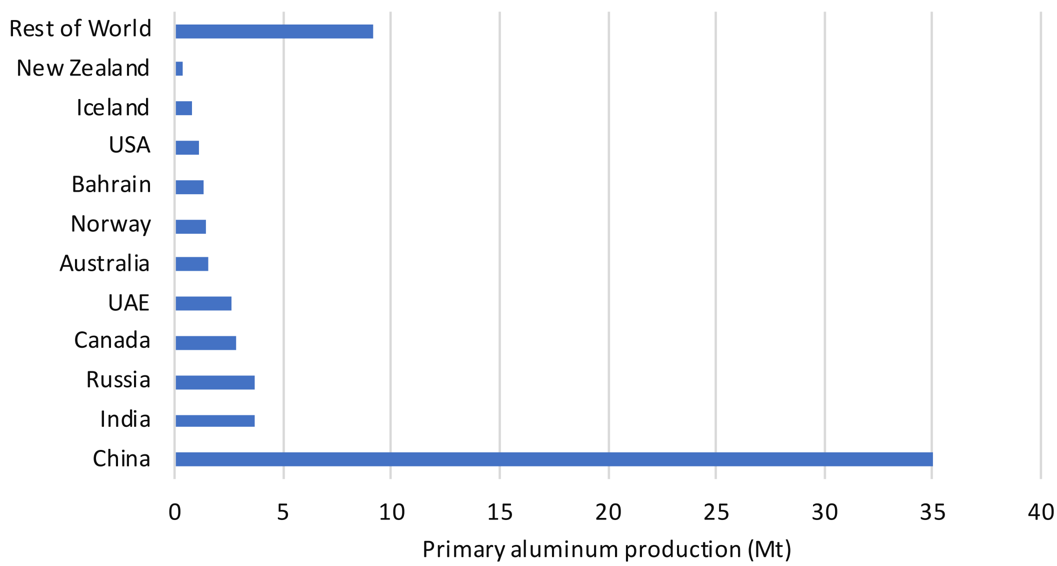


Figure 4. Top 10 aluminum producing countries in 2019 (USGS 2021)

In terms of value, the top 10 exporting countries account for 56% percent of total world aluminum export. According to the UN Comtrade database, the US, Japan, Mexico, South Korea, and Vietnam were the top five net importers (import minus export) and China, Russia, the UAE, Canada, and Norway were the top five net exporters (export minus import) of aluminum in 2019 (Table 1). The significant global trade of such a carbon-intensive commodity has substantial implications for the embodied carbon in traded aluminum, as discussed in our recent study (Hasanbeigi et al. 2018). This embodied carbon in traded aluminum often is not accounted for in national and international carbon accounting and climate policies.

Table 1. Top 10 net importers and exporters of aluminum in 2019

Country	Net Imports (million $)	Country	Net Exports (million $)
USA	11,352	China	20,314
Japan	5,815	Russia	4,643
Mexico	5,296	United Arab Emirates	4,427
South Korea	2,773	Canada	4,309
Vietnam	2,346	Norway	2,594
United Kingdom	2,235	Iceland	1,664
France	1,711	Australia	1,282
Thailand	1,505	Qatar	1,208
Indonesia	1,364	South Africa	1,130
Brazil	1,292	Mozambique	968

Figure 5 shows the top 10 alumina producing countries in the world. In 2019, these top 10 alumina producing countries accounted for 90% of global alumina production. China accounted for 54% of global alumina production, almost a similar proportion as its share in global aluminum production.

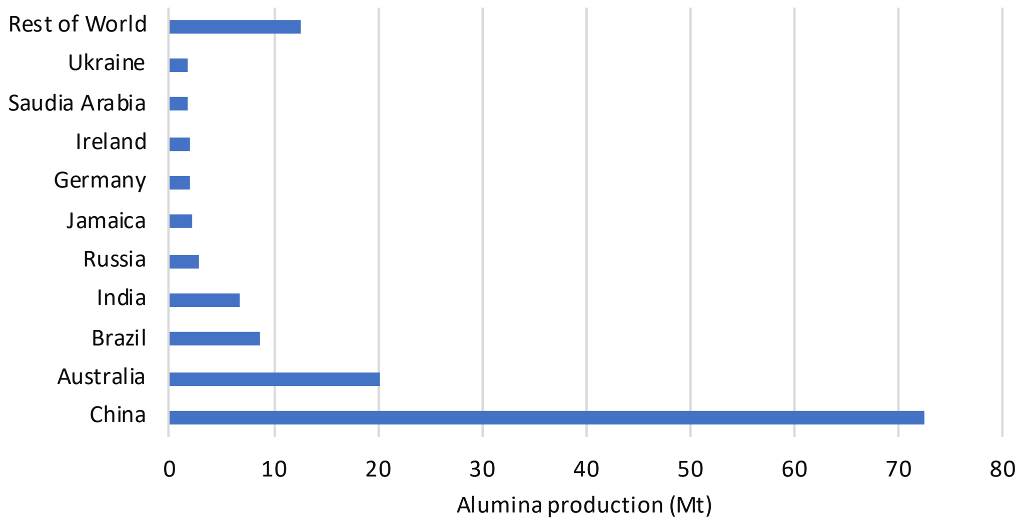


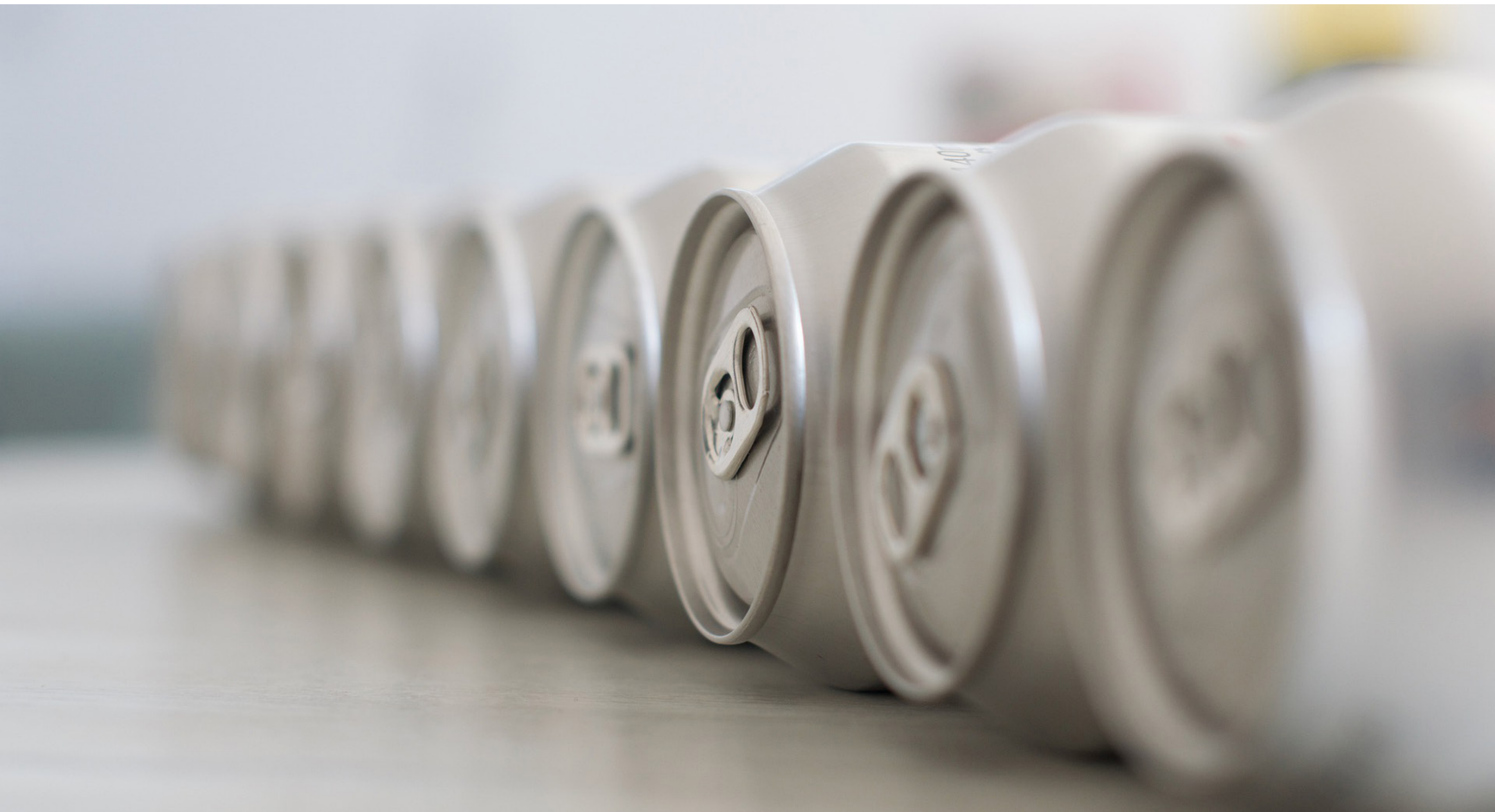
Figure 5. Top 10 alumina producing countries in 2019 (USGS 2021)

However, with the exceptions of China, India, Russia, and Australia, many aluminum-producing countries are not major alumina producers. It takes roughly two tons of alumina to produce one ton of aluminum. This means that many countries have to import significant amounts of alumina.

According to the UN Comtrade database, in 2019, the UAE, Canada, Norway, the United States, and Iceland were the top five net importers (imports minus exports) of alumina. Brazil, Jamaica, Australia, Ireland, and Turkey were the top five net exporters (exports minus imports) of alumina that year (Table 2). Because the production of alumina is an energy intensive process, the energy and CO_2 intensity estimates in this report are adjusted to reflect the energy and CO_2 emissions embodied in traded alumina, as detailed in the Methodology section in the appendix.

Table 2. Top 10 net importers and exporters of alumina in 2019

Country	Net Imports (kt)	Country	Net Exports (kt)
United Arab Emirates	5,309	Brazil	8,004
Canada	3,977	Australia	4,012
Norway	2,572	Jamaica	2,222
USA	2,268	Ireland	1,929
Iceland	1,598	Turkey	1,713
Malaysia	1,560	Sri Lanka	1,244
South Africa	1,388	Kazakhstan	774
Qatar	1,187	Indonesia	573
India	2,407	Vietnam	540
Japan	925	Greece	497



3 The Global Aluminum Industry's CO_2 Emissions

Based on the final estimated CO_2 intensity for the 11 countries covered in this study, we estimate the total energy-related CO_2 emissions from aluminum production in these countries (Australia, Bahrain, Canada, China, Iceland, India, New Zealand, Norway, Russia, the United Arab Emirates, and the United States). We calculated a production-weighted average emissions intensity for these 11 countries. We find that the aluminum industry in these 11 countries emitted 590 million tonnes (Mt) of CO_2 in 2019. These 11 major aluminum-producing countries represented 86 percent of total world aluminum production. Assuming the rest of the world produced aluminum with the average energy-related CO_2 emissions intensity of the countries in this study, then total global energy-related CO_2 emissions from aluminum production in 2019 would be 656 Mt CO_2.

We also estimate the total energy-related CO_2 emissions from each of the countries studied, based on our estimated CO_2 intensity by country and the amount of production in each country. Table 3 shows the results of this analysis, with China standing out as responsible for 67% of estimated global energy-related CO_2 emissions – more than its production share, due to the high CO_2 intensity of aluminum production.

Table 3: Total energy-related CO_2 emissions from aluminum production in the countries studied and rest of the world in 2019

Country	Energy-related CO_2 emissions from primary aluminum production (Mt)	Share from world total (%)
China	445	67%
Rest of World	66	10%
India	56	8%
Russia	26	4%
Australia	20	3%
UAE	18	3%
Bahrain	10	2%
USA	8	1.3%
Canada	6	0.9%
Norway	3	0.4%
Iceland	1	0.2%
New Zealand	1	0.2%
World	663	100%

Based on the total aluminum industry's energy-related emissions presented above and the global CO_2 emissions of 33 Gt CO_2 in 2019 reported in IEA (2020b), **the global aluminum industry accounts for around 2 percent of total global CO_2 emissions.**

It is worth highlighting that if the global aluminum industry represented a country, it would be the 10^{th} largest emitter of annual energy-related CO_2 emissions in the world.

For the 11 countries studied, we also estimate the total amount of emissions from fuel and from electricity (Figure 6). Fuel use is entirely consumed during the alumina production phase, which also consumes some electricity. We find that 19% of emissions in the countries studied comes from fuel use, while 81% of emissions come from electricity use. This indicates that decarbonization efforts in these countries should be focused on electricity, but that alumina production should also be oriented towards lower carbon fuels and even carbon capture, given the presence of carbon neutrality goals in many of the countries studied. The fuel vs. electricity mix also ranges from country to country, because some countries, like Iceland and Norway, use essentially zero-emissions electricity for aluminum production, while other countries, like India, use carbon-intensive fuels both for electricity used in the electrolysis phase and alumina production.

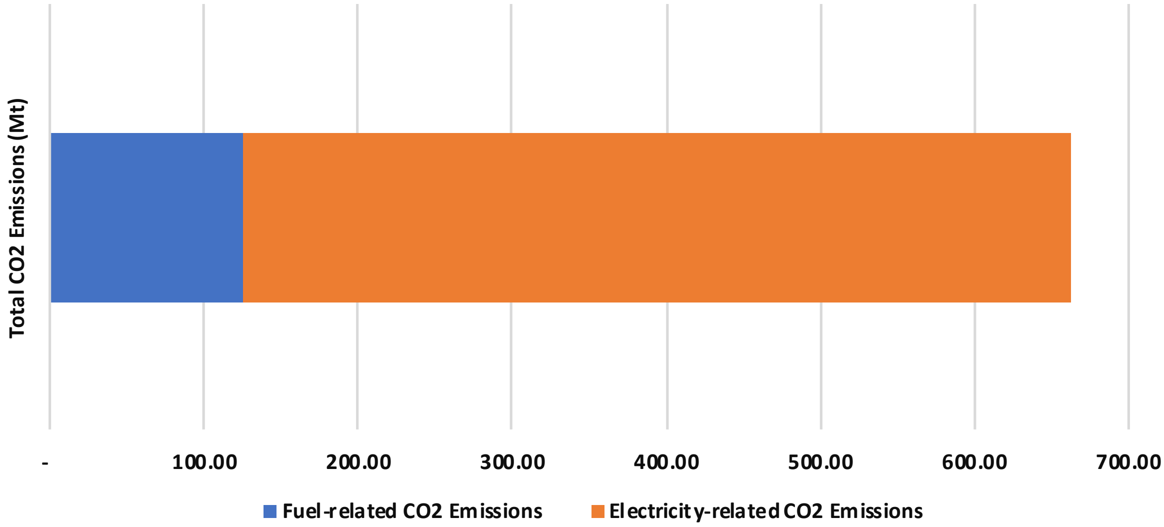


Figure 6. Total CO_2 emissions from global aluminum production (Both smelters and alumina production processes) by energy source in 2019

4 Benchmarking Energy and CO_2 Emissions Intensities of the Aluminum Industry

International benchmarking of energy intensity and CO_2 emissions intensity can provide a comparison point against which a company or industry's performance can be measured to that of the same type of company or industry in other countries. Benchmarking can also be used for assessing the energy and emissions improvement potential that could be achieved by the implementation of energy efficiency or other CO_2 mitigation measures. Also, on a national level, policy makers can use benchmarking to prioritize energy saving and decarbonization options and to design policies to reduce energy and GHG emissions.

For this study, we have conducted benchmarking of the energy intensity and energy-related CO_2 emissions intensity of primary aluminum production in 11 countries plus Europe. The 11 countries include the top 10 aluminum producing countries plus New Zealand, which is the 13th largest producer and had available data. The countries included in this study accounted for 86 percent of world aluminum production in 2019. We used 2019 as the base year for our analysis.

For the benchmarking study, we compared the energy and energy-related CO_2 emissions intensity of the aluminum industry in these 11 countries plus Europe. In addition, to understand energy use and CO_2 emissions by phase, we conducted energy and energy-related CO_2 emissions intensity benchmarking for alumina production and electrolysis, separately. To have a more accurate and fair comparison, we also took into account the embodied energy in net imported alumina for countries that are net importers when calculating energy intensity for each country.

Please see Appendix 1 for a description of the methodology. The subsections below show the results of these benchmarking analysis.

4.1. Benchmarking the Energy Intensity of Aluminum Production

Figure 7 below shows the energy intensity of aluminum smelting (electrolysis process) in kWh per kilogram of aluminum produced for twelve countries/regions. The energy intensity for aluminum smelters does not vary a huge amount between the countries/regions studied. China has a relatively new fleet of aluminum smelters, most of them installed in the past 10-15 years, resulting in relatively lower energy intensity for aluminum smelters in China (Peng et al. 2019).

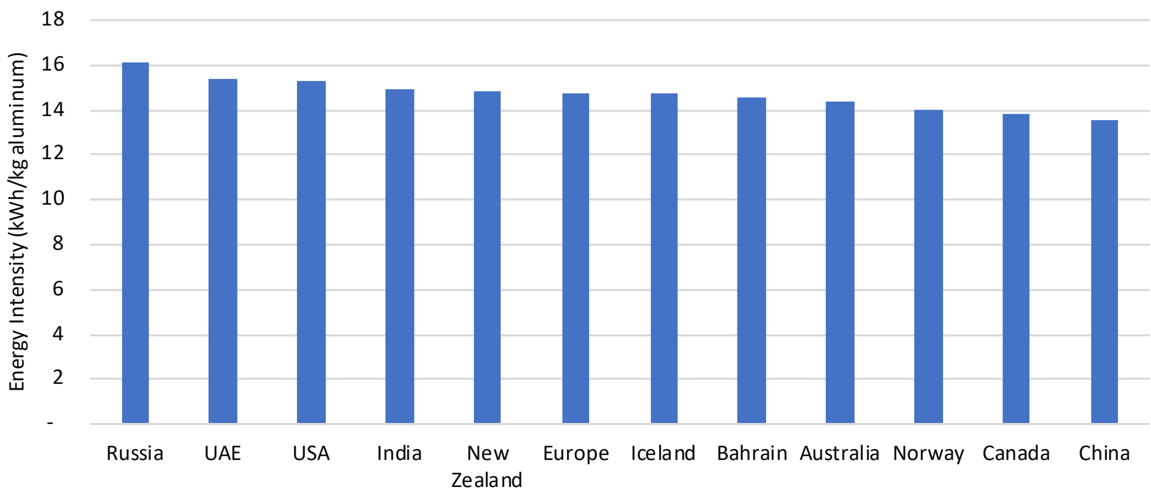


Figure 7. Energy intensity of aluminum smelters in 2019.

Figure 8 below shows the final energy intensity of aluminum production, including energy used for aluminum smelting and alumina production (both electricity and fuel use), in kWh per kilogram of aluminum produced. The energy intensity of alumina production is adjusted based on the country's net imports of alumina, using an average between the energy intensity of production within the country vs. the world average energy intensity, weighted by the ratio of domestic production to net imports. Because aluminum smelting accounts for the majority of energy use in total production, these results also do not vary widely between countries.

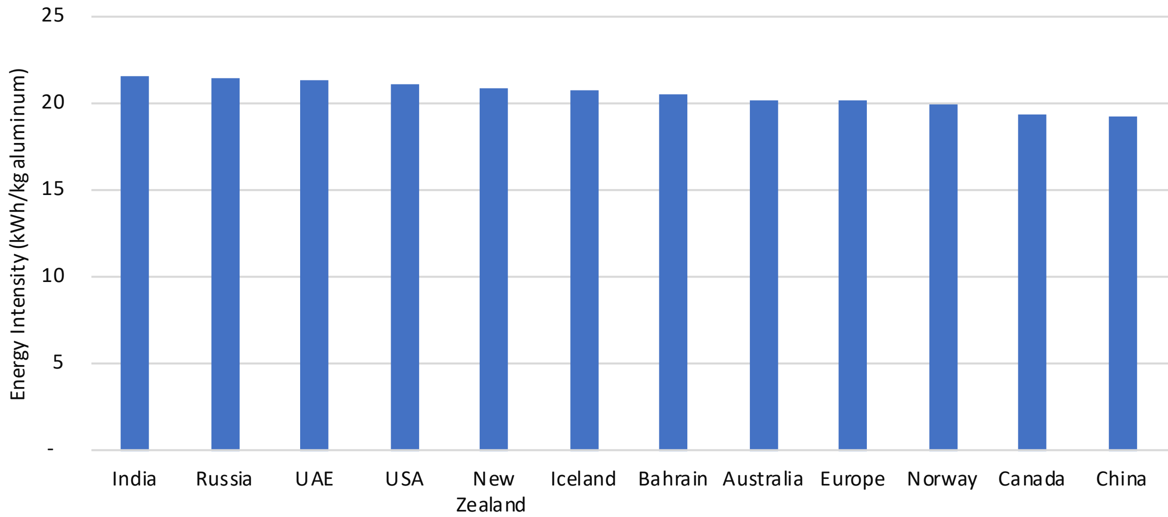


Figure 8. Final energy intensity of aluminum production in 2019.
(Note: Both smelters and alumina production processes are included. Both electricity and fuel use are included.)

4.2. Benchmarking the CO_2 Intensity of Aluminum Production

Figure 9 below shows the CO_2 intensity of aluminum production for the aluminum smelters. In some countries, captive power plants are used to generate electricity for aluminum production, while in other countries, the electricity for electrolysis primarily comes from the grid. Based on IEA estimates for the share of captive vs. grid electricity for different regions and countries, we estimated the energy-related CO_2 emissions factor for the electricity used for aluminum produced in each country. Data on captive power plants is presented in the Appendix. There is huge variation in the CO_2 intensity of aluminum smelters in the countries/regions analyzed. Iceland and Norway, which use electricity from the grid, have near-zero grid emissions factors. Canada uses a mix of low-emissions grid electricity and captive hydropower plants. On the other hand, Australia uses high-emissions grid electricity, while India uses captive power almost entirely from coal.

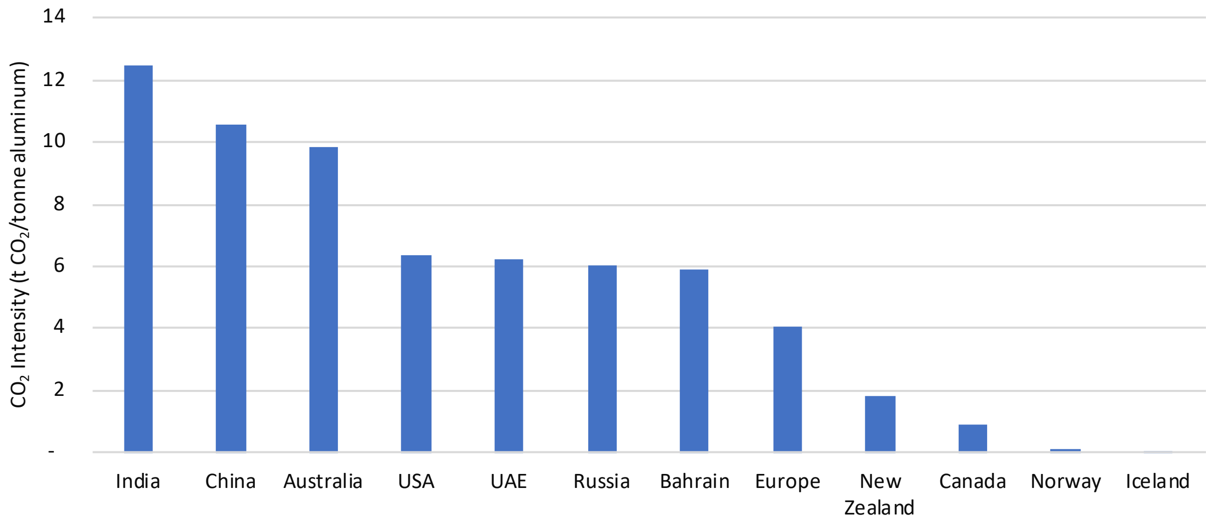


Figure 9: Energy-related CO_2 intensity of aluminum smelters in 2019 .

Figure 10 below shows the final CO_2 intensity of aluminum production, including the energy-related CO_2 emissions intensity of alumina production as well as for electrolysis in aluminum smelters. The CO_2 emissions associated with both electricity and fuel use are included. This analysis includes the embodied CO_2 associated with imported alumina for countries that rely on imports, including New Zealand, Norway, and Iceland. Other factors affecting the CO_2 emissions intensity of the aluminum industry are discussed in the next section.

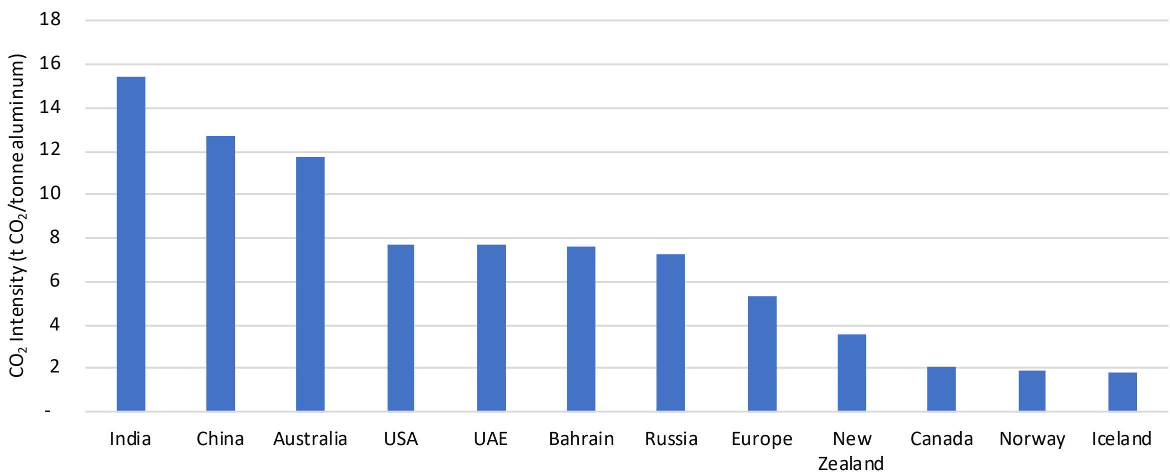


Figure 10: Final energy-related CO_2 intensity of aluminum production in 2019 .
(Note: Both smelters and alumina production processes are included. The CO_2 emissions from both electricity and fuel use are included.)

4.3. Key factors Influencing Energy and CO_2 Emissions Intensity of the Aluminum Industry

In this sub-section we discuss the following factors that could explain why the aluminum industry's energy and CO_2 emissions intensity values differ among the countries. The first four factors are directly incorporated into our analysis – the fuel mix used in alumina production, the electricity grid CO_2 emissions factor, the source of alumina used for aluminum production, and the share and type of captive power used for aluminum production.

- The fuel mix used for alumina production
- The electricity grid CO_2 emissions factor
- The source of alumina used for aluminum production
- The share and type of captive power used for aluminum production
- The level of penetration of energy-efficient technologies
- The aluminum product mix in each country
- The age of aluminum manufacturing facilities in each country
- Environmental regulations
- Cost and quality inputs
- Boundary definition for the aluminum industry

While a combination of several factors can explain variations in energy and CO_2 emissions intensity of the aluminum industry across countries, some factors have larger impacts than other. Since 81% of emissions associated with aluminum production come from electricity use for the global aluminum industry, the electricity emissions factor has the most significant impact on the CO_2 emissions intensity of the aluminum industry. It is difficult and sometime not possible to quantify the impact of each factor on energy and CO_2 emissions intensity of aluminum production across different countries. Nonetheless, even a qualitative discussion of these influencing factors can help the reader to better understand the reasons behind variations in energy and CO_2 emissions intensity among the countries studied.

The fuel mix used for alumina production

The share of different fuels used for alumina production in the countries studied is an important factor that influences the industry CO_2 emissions intensity because some fuels are more carbon intensive than others. For example, the higher share of natural gas used in Canada has helped the lower the CO_2 emissions intensity of alumina production relative to production in India and China, which almost entirely use coal. Natural gas has a significantly lower emissions factor per unit of energy compared to coal.

The electricity production CO_2 emissions factor

In addition to the share of fuels used directly for alumina production, the fuel mix for power generation to produce electricity used in aluminum industry in each country is an important factor when we compare the CO_2 emissions of the aluminum industry in the countries. The power generation fuel mix is critical because electricity used for the electrolysis stage represents the largest share of energy use and CO_2 emissions for the aluminum industry, as shown in Figure 5. Some countries, like Iceland and Norway, produce almost all of their electricity from hydropower, which does not generate direct CO_2 emissions. Thus, the fuel mix for power generation to produce electricity for the aluminum industry, and as the result the emissions factor of the power generation (kg CO_2/kWh), plays the most important role when comparing the CO_2 emissions of the aluminum industry in these countries. Since 81% of emissions from aluminum production are associated with electricity use, the most important measure to decarbonize aluminum industry is decarbonization of the electricity used in aluminum production.

The source of alumina used for aluminum production

Some countries rely entirely on imported alumina for domestic aluminum production, while other countries are major producers of both alumina and aluminum. Since the fuel mix used for alumina production varies from country to country, the share of imported vs. domestically produced alumina also plays a role in final CO_2 emissions intensity for each country.

The share and type of captive power used for aluminum production

Due to the need for massive amounts of electricity to produce aluminum, many aluminum smelters have on-site “captive” power plants. The aluminum industries in some countries and regions use captive power more than others, which use more grid electricity. For example, according to the IEA, aluminum smelters in Asia rely almost 100% on captive power, while those in Europe tend to use electricity drawn from the grid (IEA 2020a). Based on the fuel used to generate electricity at the captive power stations, and the share of captive power vs. grid electricity used in a given location, the CO_2 emissions intensity of aluminum production can vary from country to country.

The level of penetration of energy-efficient technologies

Data on penetration of energy-efficient and CO_2 emissions reduction technologies and practices in countries are scarce and not fully comparable. The types of information available in these countries differ, so direct comparison of the penetration of certain technologies is not possible. The application of energy-efficient and CO_2 emissions reduction technologies depends on factors such as raw materials used, energy sources, energy and operation costs, product mix, and the regulatory regime in the country.

The aluminum product mix in each country

Primary aluminum production typically produces ingots that may then be rolled, casted, or otherwise transformed into final products or intermediate products for further processing. Different aluminum products have different energy requirements in the rolling/casting/finishing processes. Therefore, the product mix in a country is another key factor that could influence the relative CO_2 intensities across countries. It should be noted that these rolling/casting/finishing processes are not included in the boundary of this study and we only focused on electrolysis and alumina production, which account for most of the energy used in the aluminum industry.

The age of aluminum manufacturing facilities in each country

As plants age, there may or may not be updates to manufacturing processes and equipment. In addition, newer plants tend to be more efficient. This results in a range of energy and emissions intensities among aluminum production facilities around the world.

Environmental regulations

There are differing environmental requirements from country to country. Environmental regulations can affect industry CO_2 emissions intensity by incentivizing different operational and equipment choices – for example, the EU emissions trading system regulates the aluminum industry and is meant to incentivize lower carbon production. In addition, as more and more countries set net zero emissions targets, there will generally be pressure across the aluminum industry to decarbonize.

At the same time, operation of some pollution control equipment requires additional energy, which can also add CO_2 emissions.

Cost and quality of inputs

The price of inputs including energy (especially electricity), labor, and raw materials are key components of managing costs in the aluminum industry. Changing energy and materials sources in order to optimize costs can affect the CO_2 and energy intensities of a plant. Also, the lower cost of energy, especially electricity, in some countries provides less incentive for energy optimization and increases the payback period for energy efficiency projects. In addition, electricity reliability is key for aluminum plants, as electricity outages can cause loss of electrolysis cell life. The reliability of grid supply in different areas may also be related to the decision to use captive power, which affects the overall CO_2 intensity of aluminum production, as discussed above. Finally, it is important to note that market prices for aluminum fluctuate over time in response to demand. When demand is strong and prices are high, there may be less incentive to use or invest in energy and cost-saving technologies.

Boundary definition for the aluminum industry

The boundary definition for the aluminum industry might vary from country to country in their energy statistics. For example, some countries may report the total energy used for aluminum production, while others may report only electricity use, since it makes up the majority of energy used for smelting.

5 Conclusions

In this study we conduct a benchmarking analysis for energy and energy-related CO_2 emissions intensity of the aluminum industry among the largest aluminum-producing countries. We break down the energy and CO_2 intensity of aluminum production into the alumina production phase and electrolysis process. Together, these phases represent the vast majority of energy use and 96% of GHG emissions associated with aluminum production.

Our results show that the aluminum industry in India, Russia, and the UAE have the highest energy intensity, while India, China, and Australia have the highest CO_2 intensity. On the other end, Norway, Canada, and China have the lowest energy intensity, while Canada, Norway, and Iceland have the lowest CO_2 intensity. Countries with low-emissions grid electricity and low-carbon captive power have much lower CO_2 emissions intensity due to electricity representing 81% of emissions from the countries studied. While aluminum smelters in China are highly energy efficient, the use of coal-based captive power and coal-heavy grid electricity lead to China having the thjird highest CO_2 intensity overall.

In view of the projected continuing increase in absolute aluminum production and the need for deep decarbonization of the aluminum industry to meet Paris Agreement targets, future reductions in absolute energy use and CO_2 emissions may require innovation beyond technologies that are available today, as well as additional policies and regulation. New developments will likely include different processes and fuels. Since 81% of emissions from aluminum production at the global average level come from electricity use, the most important measure to decarbonize the aluminum industry is decarbonization of the electricity used in aluminum production in key countries.

The most important measure to decarbonize the aluminum industry is decarbonization of the electricity used in aluminum production.

It should be noted that top ten aluminum producing countries account of 86 percent of global aluminum production. Therefore, substantial actions are needed by these few countries in near, medium, and long term in order to achieve net zero carbon emissions by 2050.

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Appendices

Appendix 1. Methodology

For this study, we have conducted benchmarking of the energy intensity and energy-related CO_2 emissions intensity of the top eleven aluminum producing countries, plus Europe. The eleven countries combined accounted for 86 percent of world aluminum production in 2019. We used 2019 as the base year for our analysis, collecting data where possible for that year. Although more recent data was sometimes available, given the effects of the COVID-19 pandemic in 2020, we focused on the prior year.

Fuel emissions factors are from the IPCC (2006) and electricity grid CO_2 emissions factors in the studied countries in 2019 are shown in Figure A.

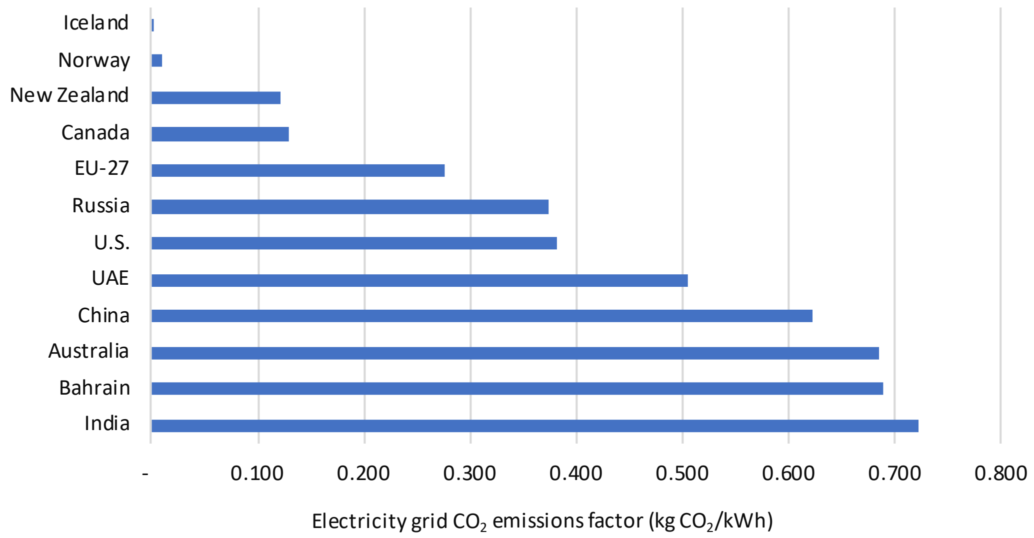

Figure A1. Electricity grid CO_2 emissions factor the countries/regions studied (Carbon Footprint 2020, IEA 2021, European Commission 2021).

First, we searched for data on the energy intensity of electrolysis, making sure that the system boundaries were as similar across sources as possible. In some cases, regional estimates were available and one country within that region did not have available data. For such cases, we used a production-weighted average to estimate the contribution of energy intensity of electrolysis in the country with missing data to the regional average.

Next, we searched for data on the energy intensity of alumina production, taking a similar approach as for the energy intensity of electrolysis. Because many countries that produce aluminum need to import alumina, we adjusted the energy intensity of alumina production in those countries for the energy intensity of traded alumina, which we assumed to be the world average. Using UN Comtrade data, we identified the share of imported alumina based on net imports and production data. Then, we used those shares to estimate a weighted average energy intensity based on domestic production and imported alumina.

Some of the key sources we used to estimate the energy intensity of smelters and alumina production are listed below (see references section):

- IAI (2021c)
- European Aluminium (2015)
- Aluminium Association of Canada (2021)
- Australian Aluminium Council (2020)
- Norway Statbank (2020)
- Aluminium Bahrain (2018)
- Orkustofnun (Iceland National Energy Authority) (2020)
- Bureau of Energy Efficiency, India Ministry of Power (2017)
- U.S. Department of Energy (2017)

For estimating the CO_2 intensity of electrolysis, we first identified which countries used captive power plants for aluminum production, and the share of electricity coming from captive power in those countries. We estimated the emissions factor for captive power in each country based on the reported fuel mix of captive power plants. Using the share of captive power vs. grid electricity, and the grid emissions factor of each country, we estimated the weighted average CO_2 intensity of electricity used for aluminum production.

For estimating the CO_2 intensity of alumina production, for countries that only imported alumina, we used the world average value. For countries that produced alumina, we used IEA data on non-ferrous metal fuel consumption and associated fuel emissions factors to estimate the average CO_2 intensity of fuel used to produce alumina in each country.

Appendix 2. Description of aluminum production

Aluminum ore (bauxite) is first processed into alumina via the Bayer process. Alumina is then reduced to aluminum via the Hall-Héroult process. The Hall-Héroult process is briefly explained in the section below. Figure A2 is a simplified diagram. The following subsections describe the main production steps of aluminum, from mine to metal.

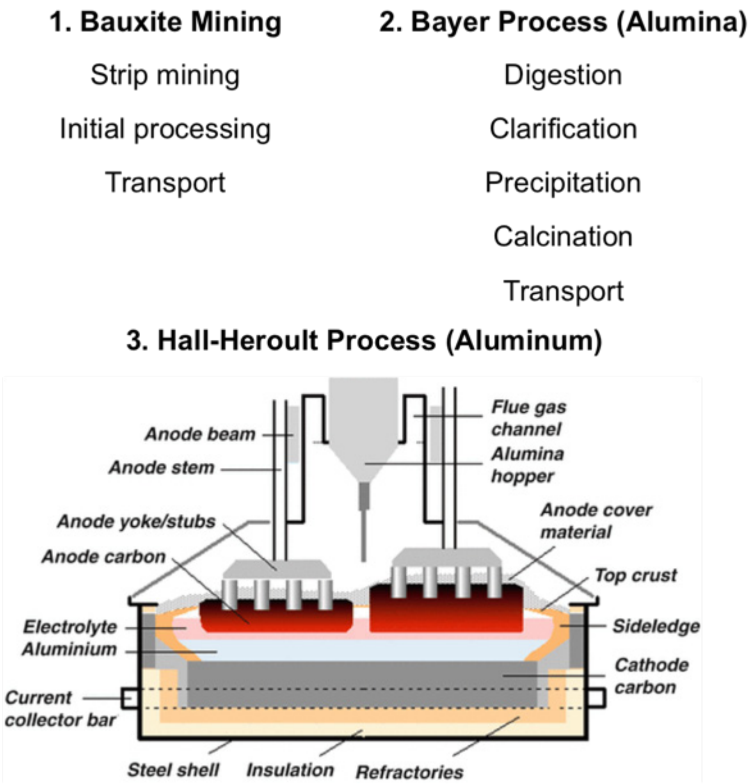

Figure A2. Diagram of the major steps of primary aluminum production (image source: Haarberg 2014)

Bauxite Production
Aluminum is abundant in the earth's crust, but since the metal is highly reactive, it typically exists in its oxidized form. The term 'bauxite' refers to ores that contain a high (over 35%) concentration of aluminum hydroxide minerals.The three main types of bauxite are gibbsite, böhmite and diaspore. Böhmite and diaspore have a different crystalline structure and hydrate content, and require higher temperatures and pressures than gibbsite for processing (Tabereaux and Peterson 2013).Bauxite mining begins with mechanical removal of theoverburden layer covering the bauxite, which ranges from 2-20 meters in depth (Wagner et al. 2010). Since bauxite deposits tend to be soft and earthy, high-energy operations like drilling and blasting are not used as intensively as for some other ores. In addition, bauxite mines are often open-pit mines, eliminating the need for energy-intensive ventilation and de-watering processes. Loading and hauling is the most energy-intensive process in bauxite production, usually carried out by diesel-powered trucks and excavators (Norgate and Haque 2010). Bauxite requires minimal processing before moving to an alumina production plant – bauxite may be crushed, ground, and beneficiated, with beneficiation used mainly to remove clay. This can be achieved by washing, wet screening, cycloning, or sorting the bauxite. The estimated primary energy demand for producing bauxite is about 278 kWh/ton (1 GJ/ton) (The Aluminum Association 2013).

Alumina Production
The subsections below describe the Bayer Process, which refines bauxite into alumina and is the main alumina production process used throughout the world. As a rule of thumb, about two tons of bauxite are required to produce one ton of alumina, and two tons of alumina are required to produce one ton of aluminum.

Digestion
Mined bauxite is first washed and crushed in order to increase the surface area available for reaction. Some bauxite goes through desilication to remove impurities. The bauxite is then dissolved in a series of high-pressure digesters at either low temperatures (~100 °C) or high temperatures (~250 °C) with the addition of a caustic soda solution. Low temperature digestion of gibbsite bauxite requires 2083-3333 kWh/ton (7.5-12 GJ/ton), while high temperature digestion of böhmite or diaspore bauxite requires 3055-5000 kWh/ton (11-18 GJ/ton) (Tabereaux and Peterson 2013).

Clarification and Precipitation
Clarification separates solid bauxite residue ('red mud') from the desired sodium aluminate. The sediment sinks to the bottom of settling tanks, and is then removed and washed. The sodium aluminate solution is then filtered further. Cooling the sodium aluminate solution and adding mineral crystals leads to precipitation of hydrated alumina crystals ($Al(OH)_3$). Cyclones or gravity classification tanks separate coarse crystals out for calcination.

Calcination
These coarse crystals are baked in calciners at high temperature (900-1300 °C) to remove water of hydration and produce metallurgical-grade-purity alumina (Al_2O_3). Alumina calciners use a range of technologies, including gas suspension calciners (GSC), fluidized bed calciners (FBC), and rotary kilns. The final alumina product is then transported to aluminum smelters. The aluminum industry is discontinuing rotary kilns in favor of stationary calciners (GSC and FBC types), which consume about 33% less energy (3.0 GJ/ton alumina compared with 4.5 GJ/ton alumina). The calcination step requires about 25% of the total energy in the Bayer Process.

Aluminum Production
The subsections below describe the Hall- Héroult process of aluminum smelting, and outline the major determinants of its energy use and environmental impact.

The Hall-Héroult Process

The Hall-Héroult process for electrochemical reduction of alumina to aluminum was first patented in 1886, and it is still the main method of aluminum production today. Electrolysis takes place in a Hall-Héroult cell, or pot, which is typically a shallow rectangular steel basin from 9 to 18 meters long depending on amperage, lined with carbon. In order to keep various materials molten, the cells operate at around 950-960 °C. Inside the cells, a molten cryolite (Na_3AlF_6) electrolyte or "bath" serves as the conductor for the electric current running through the carbon anode to the positively charged surface of newly formed molten aluminum on the carbon lining (the cathode). Aluminum fluoride (AlF_3) is added to the solution to maintain optimal chemistry and lower the electrolyte's freezing point. Beneath the carbon lining, steel bars pick up the electric current and take it to the next cell. Long rows of cells are connected in an electrical series (potline), sometimes up to around 400 cells per potline and more than one kilometer long. Automatic feeders continuously add alumina to cells, which dissolves in the molten electrolyte. As the electrical current passes through the solution, the dissolved alumina is split into molten aluminum ions (Al^{3+}) and oxygen ions (O^{2-}). The oxygen consumes the carbon in the anode blocks to form carbon dioxide.

Molten aluminum produced at the cathode surface is regularly removed by siphon from the top of the cell. Electrolysis through the Hall-Héroult process is by far the most energy-intensive step of primary aluminum production.

Although the Hall-Héroult process was first developed over 100 years ago, it is still essentially the only commercialized production route for primary aluminum. The production of secondary aluminum from scrap and recycled aluminum is becoming an increasing source of the metal – in 2011, the amount of remelted and recycled aluminum approximately equaled the amount of primary aluminum produced (Tsesmelis 2013).

Carbon Anode Production

The overall reaction takes place at the bath-metal interface as the reduction of alumina and the oxidation of the carbon anodes, producing pure aluminum and carbon dioxide. This reaction means that over time, the carbon anode is consumed. Consequently, the carbon anodes must be replaced about once a month in most aluminum smelters. There are two types of anodes: Soderberg anodes and pre-baked anodes. Currently, all new aluminum smelters use pre-baked anodes, which are so named because baking them bonds the calcined petroleum coke and coal tar pitch together. Aluminum or copper rods attached to a steel yoke assembly are connected by steel stubs (inserted and secured by molten cast iron) into the anodes to deliver electricity. The anodes are replaced before they are completely consumed. Anode production is itself an energy-intensive process, require about 444 kWh/ton (1.6 GJ/ton) under best-practice conditions (Worrell et al. 2007)

Anode-Cathode Distance

The anode-cathode distance (ACD) is the distance between the electrode surfaces in a given Hall-Heroult cell. It averages around 4-5 cm. The ACD is one of the main determinants of the voltage necessary for the current to pass through the bath and drive electrolysis. Voltage, in turn, determines electrical energy requirements (with a constant amperage cell operation). A lower ACD reduces voltage, but if the electrode surfaces come into contact, the cell will short circuit. Magnetohydrodynamic (MHD) forces in the cell cause the surface of the molten aluminum to deform and in some cases undulate, and the ACD must be wide enough to accommodate this motion.

Operating Temperature
The molten bath chemistry is a major determinant of the temperature at which a Hall-Heroult cell operates (typically 950-960 °C). The temperature affects the electrical resistance of the bath and thus the total cell voltage. A lower cell temperature also reduces the solubility range for alumina, decreasing cell operating efficiency.

Anode Effects
Current Hall-Héroult cells are susceptible to anode effects, which are triggered by depletion of the alumina concentration. When this concentration becomes too low for normal cell operation, an anode effect occurs, characterized by formation of carbon monoxide and perfluorocarbons (PFCs) and smaller amounts of carbon dioxide, the ordinary reaction product. The bottom surface of the anode becomes covered by a gas film, leading to high voltages, typically 30 to 40 V (over usual levels of 3.5-4.5 V). The smaller the anode surface immersed in bath, the higher the anode effect voltage. Anode effects thus lower cell operating efficiency, cause a spike in energy requirements, and evolve potent greenhouse gases.

Casting, Rolling, and Extrusion
The molten aluminum produced from the Hall-Heroult process is typically cast into ingots, which are then transported to foundries and other processing plants to be transformed into alloys or final products. Aluminum foundries may re-melt the ingots to produce desired alloys, which are then cast into the required shapes for consumer or industrial products. The malleability of aluminum metal means it is also well-suited for rolling into thin sheets. Aluminum may also be extruded into its final shape. The products from the mills may be further processed in various ways, such as coating or painting. Casting, rolling, and extrusion mills consume fossil fuels for reheating the aluminum ingots, as well as electricity, leading to indirect greenhouse gas emissions.