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Competitiveness of Global Aluminum Supply Chains Under Carbon Pricing Scenarios for Solar PV

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Foreword

Aluminum is a crucial metal for the energy transition. It is necessary for many low-carbon technologies such as wind turbines, batteries, electrolyzers for renewable hydrogen, carbon storage for low-carbon hydrogen, transmission wires, and hydroelectric plants and it's a major material for solar PV technologies. Aluminum accounts for more than 85 percent of most solar PV components being used for the frames of the panels as well as in the cells and attachments. And with projected increases in solar PV deployment, demand for aluminum is expected to rise.

Over the past decade, relatively low global prices and strong competitive pressures have contributed to the closure and mothballing of capacity in many countries involved in the aluminum industry. Developing new aluminum production capacity in new countries is also proving challenging because of high capital, energy, and input costs.

Aluminum production often comes with a large carbon footprint. Greenhouse gas emissions arise across the supply chain, from bauxite mining, through alumina refining to aluminum smelting. The importance of aluminum to the low-carbon energy transition, the competitiveness challenges many producers face, the volatility of its market, and its potentially high emissions warrant further research into the metal, its competitive position (especially in the context of climate policy such as carbon pricing) and alternative decarbonization options.

This report examines the competitiveness of aluminum production in the context of potential carbon prices. The report uses public and industry data on the capital and operating costs of producing bauxite, alumina, and aluminum in different locations, along with country-specific data on energy use and greenhouse gas (GHG) emissions to examine these questions. Key findings highlight that, at historic price ranges, value addition opportunities for new and existing smelters are limited when carbon prices are applied. Decarbonization across the aluminum supply chain is therefore needed to retain competitiveness and promote diversification of suppliers. Options exist such as using more renewable-generated electricity to power smelters or using carbon-free anodes. However, more investment and research and development (R&D) is needed, especially in non-electricity related technology, to decarbonize the entire aluminum supply chain, and in the process ensure producers remain competitive. Finding ways to increase the supply of recycled aluminum, by increasing scrap collection and encouraging circularity is also essential to decarbonizing the aluminum sector.

Ultimately, governments and the private sector need to be proactive and collaborate to ensure aluminum can be supplied at a competitive price and with the lowest possible climate, environmental and social footprint, thus enabling the deployment of the technologies needed for the energy transition.

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Executive summary

Introduction

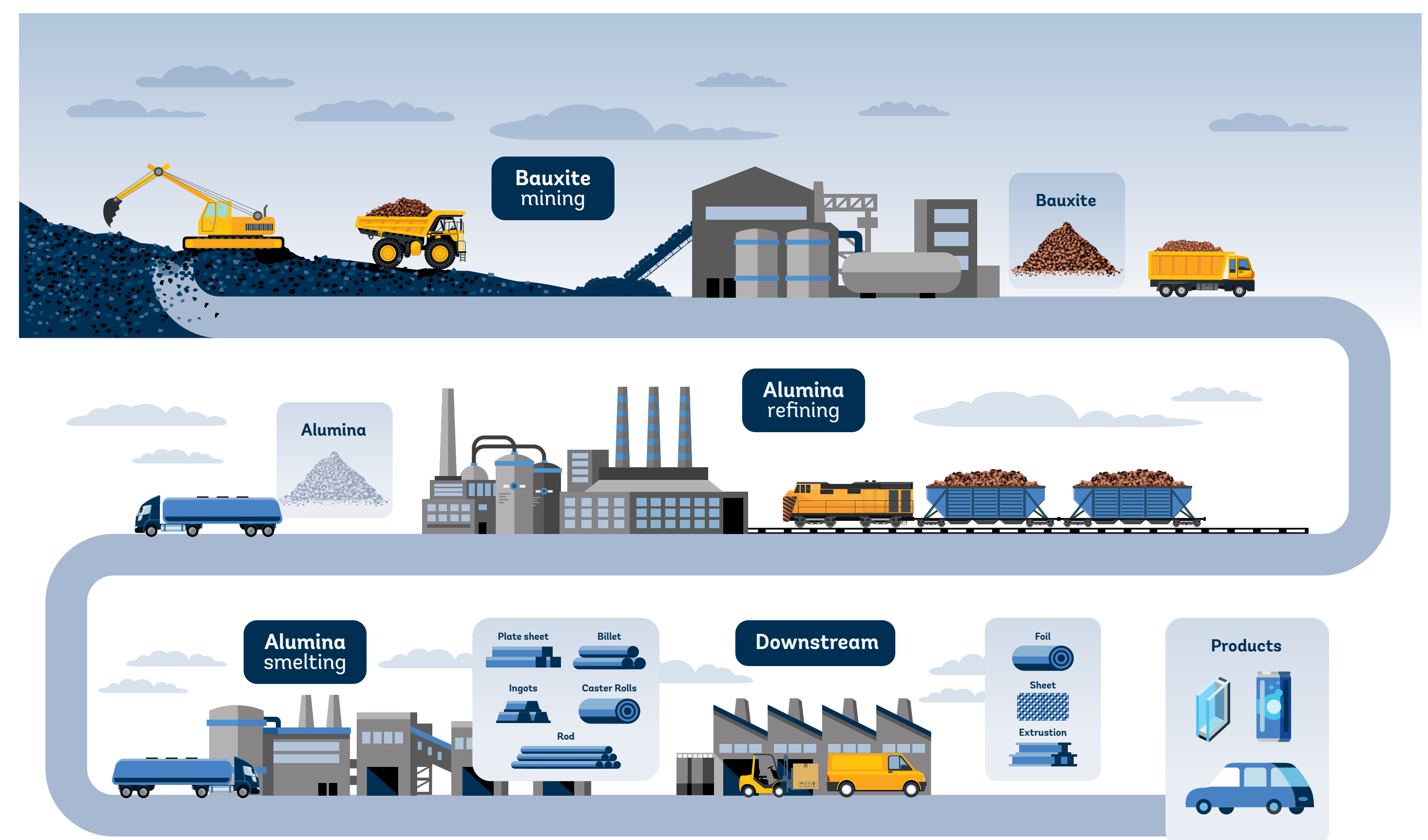
Aluminum is a critical metal for the energy transition. It is necessary across many low-carbon technologies such as wind turbines, batteries, electrolyzers for renewable hydrogen, carbon storage for low-carbon hydrogen, transmission wires, and hydroelectric plants; and it's a major material for solar PV technologies. Recent studies have noted the increased demand for the metal, with the potential exponential rise in particular from solar PV (for example, Hund et al 2020; IEA, 2021 Lennon et al. 2022). The sourcing of this aluminum is a critical question, not least from an emissions perspective, with the production of aluminum accounting for approximately 2 percent of total annual greenhouse gas (GHG) emissions (S&P Global 2021).

The production of aluminum requires three stages: extraction of bauxite, refining of bauxite into alumina via the Bayer process, and then smelting into aluminum via the Hall-Héroult process (Figure 1).

Different regions and countries play varying roles in these stages. While low- to middle-income countries as well as high-income countries are represented in the first two stages of extraction and refining of bauxite, middle-income countries (MICs) such as China and India smelt the majority of the world's aluminum and represent most of the growth in capacity since 2008. Low-income countries (LICs) such as Guinea are mainly represented in the first and second stages; LICs smelt less than 1 percent of the world's aluminum despite countries such as Guinea holding significant reserves of bauxite. The expected growing demand for aluminum raises the question of whether and how it can be met, and if LICs and MICs can benefit from it.

The adoption of carbon pricing is gaining momentum around the world, with more than 60 carbon tax and emissions trading programs introduced at the regional, national, and subnational levels. Major carbon pricing initiatives have been launched in China and Germany, and others are planned for this year including the

Figure 1: Aluminum production process



European Union's carbon border adjustment mechanism (CBAM). While only about 20 percent of global emissions are covered by carbon pricing programs, they have the potential to impact the aluminum production value chain at different points.

The potential application of carbon pricing to the aluminum sector highlights the intertwined challenges of competitiveness and decarbonization facing the sector. Modeling was conducted to estimate the potential value-addition opportunities of different aluminum supply chains. It used public and industry data on the capital and operating costs of producing bauxite, alumina, and aluminum in different locations, along with country-specific data on energy use and GHG emissions.

The modelled supply chains start with bauxite from two major bauxite producers such as Brazil or Guinea, representing 30% of global production, and then go through a range of alumina and aluminum locations, estimating emissions and value-addition under a range of scenarios regarding prices, global carbon prices, and electricity mixes (based on International Energy Agency [IEA] scenarios). The modeling led to the identification of trends and recommendations for value-addition and decarbonization that would help retain value in the presence of carbon prices for both brownfield (existing) smelters and greenfield (new) smelters. Solar PV was used to illustrate the impact on manufactured goods of the costs and GHG emissions of primary materials such as aluminum, owing to the fact that aluminum accounts for more than 85 percent of most solar PV.

Value-Addition

The aluminum industry consists of a range of producers, with many established refineries and smelters operating facilities that have been producing aluminum for decades. Over the past decade, relatively low global prices and competitive pressures have contributed to the closure and mothballing of capacity in many countries. Understanding how existing producers may respond to carbon prices is therefore important for ensuring the industry responds to market changes effectively and remains competitive. The modeling analysis highlights that, at historical ranges of aluminum prices, value-addition opportunities exist for brownfield smelters in high-income countries (HICs) and middle-income countries (MICs), with the latter showing similar levels of value-addition for smelters using electricity from either hydropower or fossil fuels. However, once a global carbon price is assumed – and without significant changes in technologies deployed - these value-addition opportunities decline, most significantly in fossil fuel–fired producers such as China and India. Aluminum producers in fossil-fuel intensive economies see their costs rise by more than 30 percent with a US$50 per ton carbon price and by almost 60 percent with a US$150 per ton carbon price. Cost rises are more moderate in locations with predominantly dispatchable renewables powered smelters and countries with more ambitious electricity decarbonization goals, but they may still be significant (more than 30 percent with a US$150 per ton carbon price) without decarbonization of nonelectricity emissions across the supply chain.

These results imply that, in the presence of strong carbon prices (for example, through carbon border taxes) action may be needed across both electricity and nonelectricity emissions in all locations for producers to retain value-addition opportunities.[1] Should aluminum producers lack the ability to pass-through costs to consumers, to remain competitive all producers, including those with relatively low-emissions supply chains, will have to tackle the areas that generate the most emissions: processing, heat (especially in alumina refining) and transportation. Governments and the private sector need to come together to tackle GHG emissions along the whole aluminum value chain by eliminating the technical and economic barriers to the adoption of technologies/processes designed to reduce emissions.

1 This depends on reaction of product prices to carbon prices – more detailed economic modelling is required to fully determine the scale of this effect.

Although existing producers will likely supply a significant share of aluminum production in the near term, the prospect of growing aluminum demand raises the question of whether the economics of building new aluminum production capacity are favorable, ensuring that this new demand will be met.

The results of the analysis highlight that, at historical price ranges, many existing aluminum producers have limited value-addition opportunities from building new smelters. This is due to the high capital costs required in HICs, LICs, and in some MIC locations. Value-addition opportunities, in the absence of global carbon prices, do exist, however, in some MICs because of low capital costs and competitive energy costs (for example, China, India). However, in the presence of high carbon prices (for example, US$100+ per ton carbon), these value-addition opportunities diminish. Under IEA's Sustainable Development Scenario there is no value added for any country from building new smelters. This implies that, under historical price ranges and high carbon prices, building new smelter capacity is potentially uneconomic even when the electricity that is being used to power the smelter is low-carbon. If high carbon prices effectively deter investment in new capacity, the aluminum sector won't be able to meet the expected increased demand. This will likely result in higher aluminum prices, increasing the cost of producing solar PV and other low-carbon technologies worldwide. Higher aluminum prices may ultimately incentivize mothballed capacity to return to production. Further work is needed to quantify the scale of this potential effect on the global aluminum prices.

Developing new aluminum production capacity beyond existing producers - for example in LICs that are already bauxite and alumina producers - can be quite challenging because of high capital, energy, transport and input costs, as well as high investment risk, particularly in LICs. Concerted efforts by policymakers and the private sector are required to overcome these challenges and develop new aluminum production capacity.

Decarbonization

The aluminum industry has taken action to reduce GHG emissions on a plant-by-plant basis over the last two decades. Progress has been made in particular with respect to non-CO_2 GHG such as perflurocarbons that arise as part of the aluminum smelting process. However, at an industry level, average global GHG emissions per ton of aluminum fell only slightly, by approximately 7 percent, between 2006 and 2019. This is due in part to the shifting geography of production, with more of global production moving to fossil fuel–powered MICs, which are the highest emitters per ton of aluminum produced, with China and India accounting for well over 60 percent of total GHG emissions from aluminum production.

The aluminum sector needs to reduce its GHG emissions to help meet climate targets and create value for aluminum producing countries. The potential emergence of a differentiated market with a price differential between "green" (low-emissions) and "non-green" aluminum only highlights the need for decarbonization.

Strong and stable carbon prices can create the incentives needed for the adoption of low-carbon technologies and/or for retrofitting of existing assets to reduce GHG emissions along the aluminum value chain. Decarbonizing the electricity used in smelters is a necessary but not sufficient condition for full decarbonization of the aluminum sector. Action is also needed to tackle the remaining one third of GHG emissions arising from heat use, direct processes, and transportation. Technological solutions exist - including, carbon capture and storage (CCS), inert carbon anodes for alumina refining and medium-heat generation from biofuels, clean hydrogen and electricity - but some of these have not yet reached commercial scale, and require government support.

Governments can play a very important role in promoting the decarbonization of the aluminum value chain. In some jurisdictions, regulatory action has led to the shutdown of inefficient carbon-intensive smelters. A few of these ended up being replaced by more efficient smelters powered - when possible - by hydropower. The new smelter technologies reduce electricity requirements and process emissions - particularly of non-CO_2 emissions - and are therefore more economic when high carbon prices are in place.

In addition to regulatory measures, governments can provide fiscal incentives and/or invest in R&D to facilitate the adoption of new and emerging technologies that reduce the aluminum sector's GHG footprint. Promotion and facilitation of technology transfer should also be a key priority for policymakers and the private sector alike, because it would allow MICs and LICs to deploy the best, most efficient and lowest-emissions technologies in new and/or existing smelters/alumina refineries, leveling the playing field, and reducing GHG emissions worldwide.

Role of Recycling

Aluminum is one of the most recycled elements, with potential for near-infinite recyclability, with recycled material accounting for approximately 34 percent of annual production. Secondary production occurs from either new scrap (material produced as an offshoot of manufacturing processes) or old scrap (material used by consumers and discarded). Recycled aluminum production has a much lower carbon footprint than primary aluminum (approximately 5 percent), but there are barriers to scaling up recycling to meet the projected increase in aluminum demand. For one, more than 90 percent of globally available scrap is already being recycled, according to the International Aluminum Institute. Increasing the availability of scrap is also challenging due to the long lifetime of many of the uses of aluminum and the recovery challenges in sectors such as consumer packaging.

Implications

The results of this analysis raise questions about the ability of many existing producers to establish new aluminum facilities to meet the growing demand for aluminum from low-carbon technologies such as solar PV. First, high capital costs across most regions make establishing new capacity challenging. Opportunities for existing producers are greater in the absence of carbon prices. In the presence of high carbon prices and without action to reduce GHG emissions along the aluminum value chain many producers would struggle to generate value and to supply an increasing demand at historical price ranges. Without decarbonization then, aluminum prices would likely rise, resulting in higher costs for solar PV producers.

Second, existing aluminum producers will find it difficult to add new facilities and even operate existing ones, especially in the presence of carbon prices. Modeling indicates that at historic price levels opportunities for new producers to enter the market will likely be limited, although these may increase with higher aluminum prices. This is especially true for LICs that may face significant challenges. Without significant improvements in infrastructure, skills, and energy supply, the most significant opportunities for value-addition for LICs may be found in bauxite and alumina production. Taking action to decarbonize the electricity and heat used in the aluminum sector in LICs could help uncover more value-addition opportunities, by enhancing competitiveness and reducing the impact of carbon pricing.

Conclusions and Recommendations

At historic price ranges, installing new aluminum capacity will likely be uneconomic for most current producers. Thus, in the presence of higher future demand, increasing the supply of aluminum would require either increasing production from existing smelters or increasing prices of the product. In the presence of carbon prices and higher demand, the economics of value-addition in the aluminum supply chain decline further, even in locations where smelters use low-carbon electricity, because of the rest of the GHG emissions emitted along the value chain.Therefore, increasing the supply of aluminum at historical price ranges requires decarbonizing the sector, increasing secondary supply, increasing the value-addition in existing and new locations, or a combination of all three.

Decarbonizing the aluminum supply chain is a crucial component in achieving a low-carbon energy transition, both on its own merits and for its role as an input in a range of low-carbon technologies, including solar PV. Failing to do so raises both the emissions footprint of these technologies; and, in the presence of high carbon prices, the cost of the technologies. Addressing both electricity emissions, through the installation of low-carbon electricity generating technologies, and nonelectricity emissions such as heat and process emissions, through the use of low-carbon fuels for heat and the installation of inert anodes, is vital. Policies such as carbon prices, fiscal incentives for renewable energy deployment, research and development, and promotion of technology transfer (Table 1), can help achieve this and help create a low-carbon aluminum sector that can provide the inputs needed for the low-carbon energy transition.

Recycled aluminum has a much lower emissions intensity than primary production. However, scaling up production is a challenge owing to constraints such as the availability of scrap along with technological barriers. Policy support—in LICs, MICs, and HICs—is vital to encourage the production of secondary aluminum, such as improving scrap collection, incentivizing the industry to scale up recycling and promoting the integration of a circular economy approach to product design and manufacturing. In LICS and MICs, policymakers can work with the industry to formalize the scrap collection market by setting international standards.

Increasing value addition along the aluminum supply chain will be needed to meet the expected increase in demand. There are however several economic and technical barriers. Vertical integration of supply chains could help, but it is unlikely to be sufficient, especially in LICs. Governments and the private sector can collaborate to increase access to capital, improve infrastructure, build skills, encourage adoption of more efficient technologies, and encourage use of low-carbon energy (electricity and heat). Policymakers can also consider carbon border tax adjustments and free allocation of allowances on a case by case basis as tools to retain competitiveness.

Table 1. Recommendations on decarbonizing Al production while benefiting emerging and developing economies along the Al supply chain

Sector	Opportunity	Recommendation
Value-addition	For LICs, focusing on expanding bauxite and alumina production is likely to offer the most opportunities for value-addition For MICs, value-addition opportunities exist in re-opening closed capacity and in building new smelters	• Policy support for LICs should focus on addressing challenges by building skills, investing in energy and transport infrastructure for bauxite and alumina production, and reducing wider investment risk. • In the presence of carbon prices, decarbonizing bauxite and alumina production will be important to retain competitiveness. Decarbonization will likely be needed to address broader competitiveness dimensions, including access to markets through green certification or other programs. • For MICs, retention of opportunities for value-addition in the presence of carbon prices requires decarbonization of electricity and other emissions across the supply-chain. • Due to CAPEX challenges, policy support for re-opening and retrofitting closed capacity could be more appropriate than supporting greenfield capacity.
Decarbonization	Decarbonization of electricity is necessary but insufficient. Non-electricity emissions also must be addressed	• Carbon prices are a vital signal to producers and the industry that they must invest in new electricity- and non-electricity-related technology to decarbonize the entire Al supply chain and remain competitive. • Policy support will be needed in the demonstration, deployment, and transfer of new and innovative technologies to address remaining non-electricity emissions, particularly in LICs and MICs. • Policymakers should support the deployment of low-carbon energy sources, such as low-carbon hydrogen, biofuels, and electricity for heat, because they are largely uneconomic.
Recycling	Secondary production (recycling) can help reduce emissions, but challenges remain with scrap availability and technology barriers	• Policy support in all countries will be needed to encourage the production of secondary Al, including improving scrap collection, incentivizing scale up of recycling, and promoting the integration of a circular economy approach to product design and manufacturing. • In LICS and MICs, policymakers can work with industry to formalize the scrap collection market by setting internationally accepted standards. • Policy support is needed for innovative business models such as aluminum-as-a-service, in which Al is rented to technology developers and then recovered.

Methodological Annex

The aim of the study is to estimate greenhouse gas (GHG) emissions and the value-addition of greenfield (new build) and brownfield (existing) supply chains for aluminum arising from bauxite production. The variation in the emissions and value-added of these supply chains under different scenarios, encompassing carbon taxes and electricity mix, are also estimated. To estimate emissions, value-addition, and carbon taxes as a percentage of costs, an Excel-based model was developed based on estimates of capital and operating expenditures (CAPEX and OPEX), product prices, and electricity and non-electricity energy use and emissions, along with assumptions regarding discount rates and capital repayment. Different scenarios were then generated with changes in electricity mixes, shifting both emissions and operating costs, using the Stated Policies scenario and the Sustainable Development Scenario of the International Energy Agency (IEA). In addition, different options for powering aluminum production in China were examined.

Scope of Analysis

The scope of the analysis encompasses the aluminum supply chain through bauxite production, alumina refining, and aluminum smelting. Estimates for costs and emissions also cover carbon anode production, with emissions data for extrusion also included. Costs and emissions for port-to-port shipping of product between locations are also included; those for road transport are excluded. The analysis is based on country-level averages and thus does not capture intra-country differences in costs or emissions.

For each stage of the supply chain, the study included various countries to capture the major producers and also different types of production processes, mainly at the aluminum smelting phase. Table 1 outlines the countries included in the model.

Table 1. Production Locations by Country

	Country
Bauxite	Brazil , Guinea
Alumina	Australia, Brazil, China, Guinea, United Arab Emirates
Aluminum	Brazil, Canada, China, European Union, Guinea, Gulf Cooperation Council (GCC), India, Norway, Russian Federation

This process created estimates of value-added, emissions, and carbon taxes as a percentage of costs for 90 different supply chains. Emissions, value-added, and taxes per costs were then averaged based on location of aluminum smelting (given the importance of this stage to both emissions and costs). Countries were then aggregated on the following basis to present averages based on broad income groupings:

- High-income countries (Canada, Norway, European Union, Gulf Cooperation Council (GCC) countries)
- Middle-income countries using mainly fossil fuels for electricity for aluminum smelting (China, India)
- Middle-income countries using mainly hydroelectric power for electricity for aluminum smelting (Brazil, Russia)
- Low-income countries (Guinea)[2]

Data

Data for CAPEX and OPEX, energy use (electricity and non-electricity), and GHG emissions were obtained from industry sources based on historical estimates of suitable projects. Where historical data were not available, such as CAPEX for Brazilian and European Union aluminum smelters as well as CAPEX and OPEX for an aluminum smelter in Guinea (where none yet exists), data were drawn from similar geographic locations or modeled estimates. Estimates of shipping costs, shipping distances between ports, and emissions from shipping were drawn from Panteia[3], the International Energy Agency and Sea Distances.[4] Estimates of product prices for bauxite, alumina, and aluminum (Table 2) were drawn from literature and historical trends and are assumed constant over time and between countries. A higher price scenario for aluminum, where prices rise to US$3,000 per ton, was also modeled, based on a number of inputs such as the long-term forecasts from the World Bank (which places 2035 prices at US$2400/t) along with prices prevalent in the price peaks in early 2022.

Table 2. Pricing Assumptions

	US$ per ton
Bauxite	48
Alumina	300
Aluminum	2,250

2 Guinea represents the vast proportion of bauxite and alumina production from low-income countries therefore it is the only country included for this category. However, this does potentially limit the application of the findings to other low-income countries.
3 Panteia, Cost Figures for Freight Transport: Final Report (Zoetermeer: Panteia, 2020)
4 https://sea-distances.org/

CAPEX

In the context of the aluminum supply chain, CAPEX, or capital costs, would cover the construction of mine sites, refineries, smelters, and their associated equipment. Other key features associated with CAPEX are the discount rate and the time period in which CAPEX has to be repaid.[5] The discount rate will vary depending on the nature of the aluminum project and the underlying economic and political risks in the environment, along with the desired return of the investor.

Discount rates will be higher in jurisdictions where there is greater risk, increasing CAPEX; this trend can be seen in mining projects in developing countries, for example.[6] Capital costs will vary between countries based on the ease of establishing new facilities, the amount of regulatory and planning barriers, infrastructure costs, and the costs of procuring the equipment required in the relevant facility.

It is assumed that capital is repaid over a 15-year period of a project with a discount rate of 10 percent, assumed to be the same across all countries and converted to per ton repayments via the equivalent annual cost technique. This is a simplifying assumption made in the absence of country-specific information. It is recognized, however, that discount rates are likely to be higher in areas with higher economic and political risk; therefore, costs may be underestimated, and value-added therefore potentially overestimated, in those locations.

OPEX

OPEX covers expenditures such as key inputs, energy, and labor costs. Another critical element of OPEX is the availability of the subsidiary inputs, bauxite for alumina and alumina for aluminum. The costs of these inputs vary depending on their availability in host countries (and if not, the transportation costs to those locations), the quality of the inputs available, and international commodity prices. Vertically integrated companies can remove aspects of these factors through the co-location of facilities and the inclusion of any value-added accruing from earlier stages of the supply chain in their operations. In some locations, for example, only vertically integrated operations would make economic sense, helping to secure the benefits from locally produced bauxite, and then alumina production.

Other aspects of OPEX include the cost and availability of labor, as well as the local transportation requirements from operation to port. This can be seen in the proposed Minim Martap Bauxite project in Cameroon, where the prefeasibility study identified that transportation of bauxite from the operation through the port and then to market via road, rail, and sea accounted for 85 percent of operating costs.[7]

Value-Added

Value-added in the model is defined as the following:

$$\text{Value added} = \text{Price}_{\text{Aluminum}} - (\text{OPEX}_{\text{Bauxite}} + \text{CAPEX}_{\text{Bauxite}}) - (\text{OPEX}_{\text{Alumina}} + \text{CAPEX}_{\text{Alumina}}) - (\text{OPEX}_{\text{Aluminum}} + \text{CAPEX}_{\text{Aluminum}})$$

It is assumed that for vintage producers CAPEX has been repaid and therefore these costs are zero.

Carbon Taxes as a Percentage of Costs

Carbon taxes as a percentage of costs in the model is defined as the following:

$$\text{Carbon taxes as a percentage of costs} = \frac{\Sigma\ \text{Carbon taxes}}{\Sigma\ \text{CAPEX} + \text{OPEX}}$$

Electricity and Emissions

Future scenarios of the electricity mix were drawn from the IEA. It is assumed that in future scenarios production uses electricity at a grid average, rather than from a dedicated power facility, unless explicitly stated. Electricity mixes were drawn from both the Stated Policies (SP) scenario and the Sustainable Development Scenario (SDS) for 2030. In cases where country-level information was not available from the IEA, data for the relevant regions were used to create country-level mixes. The mixes were used to estimate grid average emissions factors for relevant countries, which in turn were used to estimate emissions under each of the different scenarios. The scenarios were also used to estimate future electricity costs based on the average levelized cost of electricity (LCOE) of the future electricity mix, with LCOE data from the IEA.

Carbon Pricing

The selected carbon price level for each scenario was identified based on the World Bank's State and Trends of Carbon Pricing reports, where a carbon pricing range was provided to achieve a 2-degree scenario. They were also identified based on the International Monetary Fund's (IMF) estimation that a carbon price of US$75 per ton of CO2 would be needed by 2030 to reach a 1.5- to 2-degree scenario. In this analysis, carbon prices range between US$50 and US$150 per ton of CO2, depending on the level of climate ambition (business as usual, SP, and SDS), and it is assumed that a global carbon tax is applied across all the identified jurisdictions within the bauxite-aluminum supply chain, including international shipping. The only exceptions are for the European Union and Norway under the present scenario, where a carbon price of US$35 (based on average 2019 prices) has already been incorporated as the European Union's Emissions Trading Scheme is in place and functioning.

Limitations

A limitation of the approach taken in the model is that, because of limited publicly available data on price variation between markets, prices are assumed to be constant over time and between countries. Should aluminum prices rise then the value-added of supply chains will increase, and vice versa with price falls. Aluminum prices in recent years have been highly volatile, and at the time of writing this report, they spiked to approximately US$3,000 per ton. The effect of this is to increase the value-added of all supply chains, assuming all producers can benefit from the price rise. Changes in alumina and bauxite prices do not change the overall value-added of the supply chain as a whole; they do, however, shift the share of value-added captured by bauxite, alumina, and aluminum producers.

A number of other factors also vary between countries and time, but they are assumed constant in this analysis for reasons of tractability and lack of relevant data. These include the discount rate, capital repayment periods, and shipping costs (and emissions). Varying these may impact both value-added and emissions of relevant supply chains. Especially critical is likely to be the constant assumption of discount rates between countries. Higher discount rates in riskier countries will increase capital costs, reducing value-added. However, in terms of results this will likely only exacerbate the trends highlighted rather than reverse the relative positioning of the value-added of supply chains. It could lead, however to additional policy recommendations such as reducing investment risk through improving foundational governance in countries with high discount rates.

In some areas, suitable data were not available, so modeled figures had to be used. For instance, future electricity costs faced by companies were assumed to be equal to average LCOEs of the projected mix. This approach potentially underestimates costs as it excludes grid management charges and company profit margins. However, it may in some areas overestimate costs since it excludes the common behavior of negotiating preferential long-term electricity contracts. Further the limited data on production costs and emission factors for low-income countries, given the lack of operations in these countries beyond Guinea, limits potentially the findings beyond the scope of the study. Individual circumstances of other low-income countries should therefore be considered when applying the results of this study.

Some aspects of both costs and emissions were also excluded because of a lack of applicable data. The most significant of these is associated with the transportation of material from mine to port and from port to refinery/smelter. This transportation may occur with either road or rail and will vary from supply chain to supply chain and from company to company. Costs are likely to be highest where road transportation is required and where significant shifting between transport modes is required (for example, from handling costs from shifting from road to sea freight). However, these are likely to be relatively small compared to other areas of costs from CAPEX and OPEX.

5 In this context, the discount rate can be seen as analogous to the cost of capital that is used to fund the project.
6 Capital costs will also rise with higher demanded returns and shorter time periods in which these capital costs need to be repaid.
7 "Minim Martap Project," Canyon Resources, https://www.canyonresources.com.au/minim-martap-project/

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