A Crossroads for Aluminum and Electrified Heavy Industry

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1. Executive Summary

For critical materials strategies to succeed, policymakers must better understand the nature of the Chinese energy-industrial system that domestic vital industries are competing against. Aluminum provides an interesting case of a large-volume commodity market and a highly electricity-intensive production process that other countries desire to participate in without quite being able to rely on the same industrial policy playbook that Chinese industry benefited from.

Some might dispute that common aluminum—a ubiquitous and globally-traded commodity—carries any special strategic importance. However, aluminum is not only key for electricity infrastructure development and aerospace and defense applications but also possesses important parallels with other strategic electricity-intensive industries that governments are currently seeking to diversify, such as high-purity polysilicon and battery graphite. Electrolytic cells similar to those at the heart of aluminum smelting are key not only for producing aluminum metal but also magnesium, copper, rare earth metals, and potentially gallium, cobalt, and decarbonized steel—technological synergies that Chinese industrial strategists have recognized for around half a century.

A survey of the primary aluminum sector reveals a number of insights. Although goods may be freely traded, today's industry landscape did not develop through free markets. Such electricity-intensive heavy industry capacity does not spring forth without explicit public sector support, and in its absence the natural market equilibrium for a given critical industrial capability may mean producing little to nothing. Affordable industrial electricity is non-negotiable, posing important tradeoffs between electricity-intensive heavy industry and data center development.

At the same time, blanket tariffs alone will not deliver industry innovation or growth. For countries hoping to start catching up with China, mastery of production requires allied cooperation. An allied effort enables both flexible trade of intermediate products and coordinated development of new facilities or major retrofits that builds fresh technical familiarity and installs state-of-the-art equipment. Lastly, while rebuilding experience with today's production techniques is important for establishing a solid base of knowledge, industrial policies must look ahead towards the commercialization of future-proof technologies that will ensure continued sectoral competitiveness a decade from now. None of this will be cheap, but policymakers inclined to balk at market interventions must recognize large capital investments as the price of admission for rebuilding atrophied industry knowledge. Efforts to more globally diversify and revitalize these strategic sectors will advance both supply chain security and progress towards more advanced, cleaner industries.

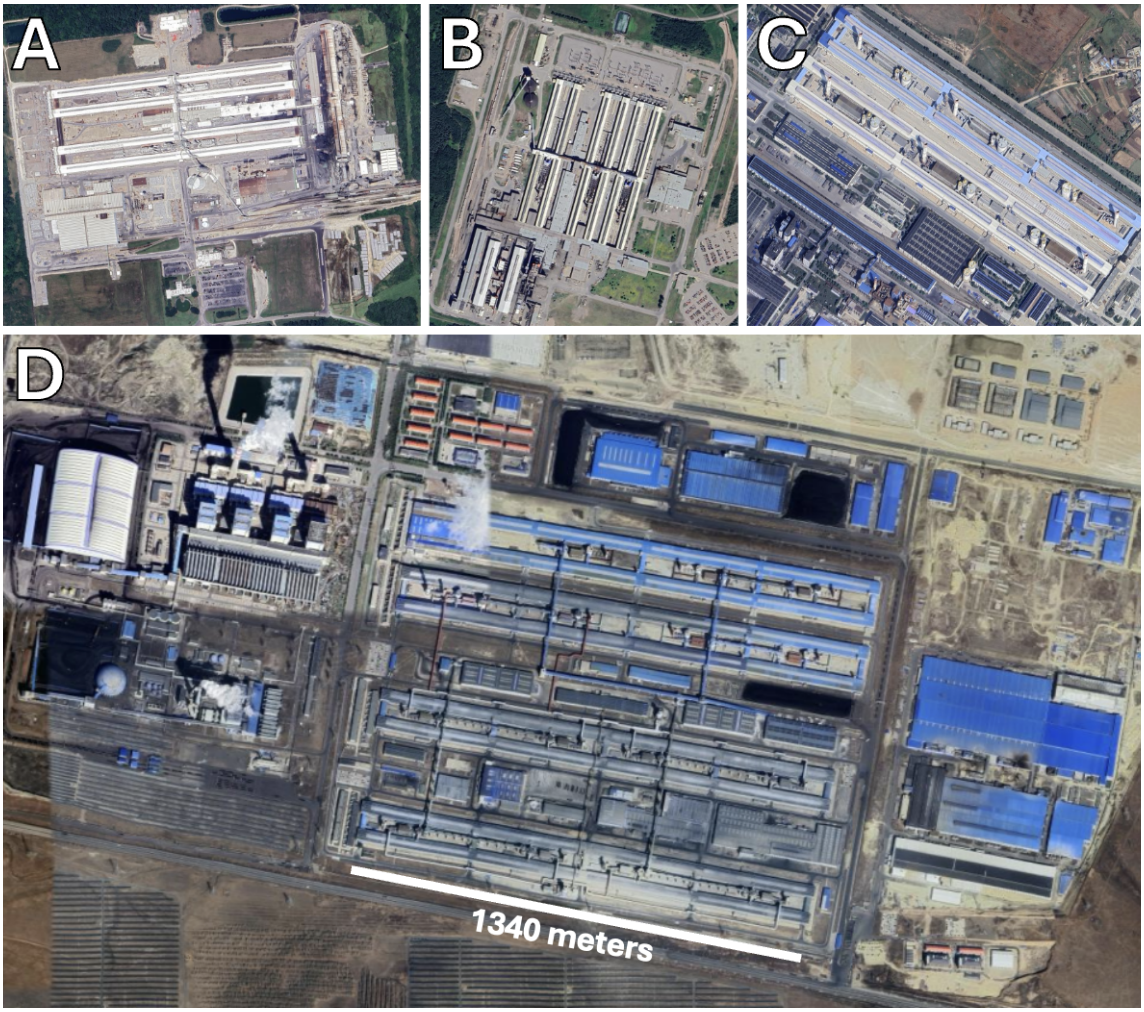

Figure 1: Examples of aluminum smelters, with satellite images adjusted to approximately the same real-world scale. Aluminum smelting occurs in the long parallel buildings, or potrooms. A) Century Aluminum's Mount Holly plant in South Carolina, U.S.A. (33.05, -80.05), commissioned in 1980 and operating Alcoa A697 228 kA cells. B) Rio Tinto Grande Baie in Quebec, Canada (48.30, -70.93), commissioned in 1980 and operating Alcoa P155 170 kA cells. C) Xinheng Group Qinghai Xinheng in Qinghai, China (36.51, 101.53), commissioned 2013 and operating SAMI 400 kA cells. D) Inner Mongolia Jinlian Aluminum in Inner Mongolia, China (45.41, 119.62), commissioned 2016 and operating SAMI SY500 500 kA cells.

2. Introduction

The standard industrial technique for smelting aluminum is known as the Hall-Héroult process, which converts aluminum oxide, or alumina, into aluminum metal via an electrochemical reaction between alumina and a carbon-based material. While seemingly niche, this process possesses important parallels with current and potential future techniques applicable throughout the critical materials sector.

Electrolytic cells are a cornerstone technology for many key current and future strategic capabilities, including the processing of rare earth elements, molten oxide electrolysis for next-generation primary steel production, magnesium smelting, and the refining of cobalt, gallium, and copper. Aluminum itself carries substantial national importance as a major input for aerospace technologies, automobiles, electricity infrastructure, construction, electronics, and consumer products.

Many other strategic industries share the aluminum sector's characteristics as a highly electricity-intensive commodity production chain, such that competitiveness in aluminum smelting likely confers competitiveness in semiconductor-grade polysilicon refining, synthetic battery graphite production, rare earth processing, nickel smelting, and more. Aluminum, as well as many of these similar strategic industries, exhibit significant geographic market concentration, imposing considerable geopolitical and supply chain risks upon countries dependent on such imports. Today, China produces around 60% of all new primary aluminum metal.

Electrolytic cells for the Hall-Héroult process are first prepared by passing high-voltage electricity through cryolite salt. This heats the salt above its melting point of 1,000°C and creates a bath of molten salt within the cell that can dissolve alumina. After dissolving alumina in the molten cryolite, large carbon anodes are inserted into the electrolytic cells, called "pots," to commence the electrochemical reaction. These anodes are typically made of petroleum coke—a solid piece of carbon produced as a byproduct from oil refining—and coal tar pitch as a binder.

As electricity continues to flow into the mixture of molten cryolite and alumina, it drives oxygen out of the alumina, letting it react with carbon in the coke. This makes carbon dioxide that escapes into the atmosphere and leaves behind molten aluminum metal which sinks to the bottom of the electrolytic cell. The Hall-Héroult process ends when aluminum smelters drain molten aluminum from the cell to be cast into various aluminum products. Smelters generally arrange pots in "potlines," linking adjacent pots in a successive series to form an electrical circuit, all housed in a distinctively long building. Typically, a large crucible with a spout carried by an overhead traveling crane is used to collect or "tap" molten aluminum from a pot.

The Hall-Héroult process is highly electricity-intensive. The Norwegian-headquartered firm Norsk Hydro currently holds the world record for the most energy-efficient pilot production of aluminum using the Hall-Héroult reaction, nevertheless consuming a hefty 11,800 kWh of electricity per ton of molten aluminum metal. By comparison, copper smelting and electric arc furnace steel recycling require only 1800 kWh and 450 kWh of electricity per ton of product, while widely-commercialized modern aluminum potline technology typically requires 12,000 kWh to 13,500 kWh per ton. Other industrial processes are still more electricity-intensive, with Siemens process refining of polysilicon to sufficient purity for solar photovoltaic cells consuming upwards of 60,000 kWh per ton of 99.9999999% (9N) polysilicon.

This white paper leverages original open-source research and structured interviews with aluminum industry technical experts to survey the current state of play in the global aluminum industry. From this overview of the primary aluminum sector, we summarize insights key to understanding the drivers of the recent and ongoing evolutions of the industry both within and outside China. Finally, we outline important realizations and next steps valuable for strengthening ex-China competitiveness in not only the aluminum sector but other critical material markets.

3. WHAT DO GLOBAL ALUMINUM SECTOR INSIGHTS CONVEY ABOUT COMPETITIVENESS?

Fundamentally, aluminum smelting and casting processes are the same everywhere

- **A proven, venerable process.** The working principles of the Hall—Héroult process and casting of aluminum billets and ingots have not meaningfully changed since the wide adoption of pre-bake carbon anode technology and gradual phaseout of smelters using less efficient Søderberg cells over the past seventy years or so.
- **Marginal but significant design improvements.** While process steps remain essentially identical, equipment has improved incrementally but meaningfully in size, safety,

efficiency, and digital controls, leaving older smelters in North America, Europe, and Oceania using older Hall—Héroult electrolytic cell "potline" technology at a disadvantage, as they may consume on the order of 12% to 20% more electricity per ton of metal.

- **Supporting upgrades and value-added casting boost economics.** Even older smelters have heavily upgraded their casthouses with automation and adoption of the latest furnace, value-added casting, auxiliary, and in some cases part fabrication equipment. Experts and industry analysis convey that direct production of value-added goods from adjacent casthouses is important for keeping such older smelters competitive.

State-of-the-art technology of comparable capability is used in new projects globally

- **New potlines? Better efficiencies.** Newer aluminum smelters benefit from the latest generation of cell technology. Some older smelters in Canada, Norway, and China have expanded or retrofitted their facilities to install newer potlines with the best available technology. Retrofits typically require a full rebuild of potline buildings due to the larger dimensions of modern cells, requiring expanded floor layouts.
- **Comparable but distinct cell technology markets.** Chinese smelters primarily use Chinese cell technology developed by the Shenyang Aluminum & Magnesium Engineering & Research Institute (SAMI), Guiyang Aluminum & Magnesium Engineering & Research Institute (GAMI), and Northeastern University Engineering & Research Institute (NEUI) and licensed for free to the Chinese aluminum industry. Outside of China, recent smelter builds have used cell technology available on the open market produced by Rio Tinto, Norsk Hydro, or Emirates Global Aluminium, though projects in a few countries operate Chinese cells. In either case, new smelters both in China and globally are installing modern high-amperage cells in the range of 400kA to 600kA with comparable production efficiencies.

Cheap electricity is a prerequisite for justifying new investments

- **Investment requires cheap power.** A favorable long-term electricity supply contract is key to capitalizing any new smelter or a significant retrofit of an existing smelter. Major smelter capital investments today are occurring exclusively in geographies with low industrial power prices, namely hydro-rich Canada, the gas-rich Middle East, hydro-rich southern China, a range of hydro and coal-powered prospects in Southeast Asia, and coal-rich India.

- **Cheap power ensures survival.** U.S. and other smelters with high electricity costs have faced the greatest risk of being priced out of the current aluminum market, as highlighted by the curtailment of Century Aluminum's Hawesville smelter in 2022 and the closure of the Magnitude 7 Metals aluminum smelter in January 2024. Meanwhile, facilities running off of clean, cheap hydropower in Canada and off of hydropower or captive coal power plants in China sit comfortably on the safer side of the global cost curve.
- **Power is the major cost center.** Electricity constitutes 30% of the production cost of primary aluminum in countries like Canada and up to 40% of the production cost of primary aluminum in the United States, representing the single largest cost center in aluminum smelting. In China, electricity can similarly account for more than 40% of the production cost of primary aluminum metal. An aluminum smelter's electrolytic potlines typically consume in excess of 90% of the total power demand for the whole facility, casthouse and anode furnace operations included.

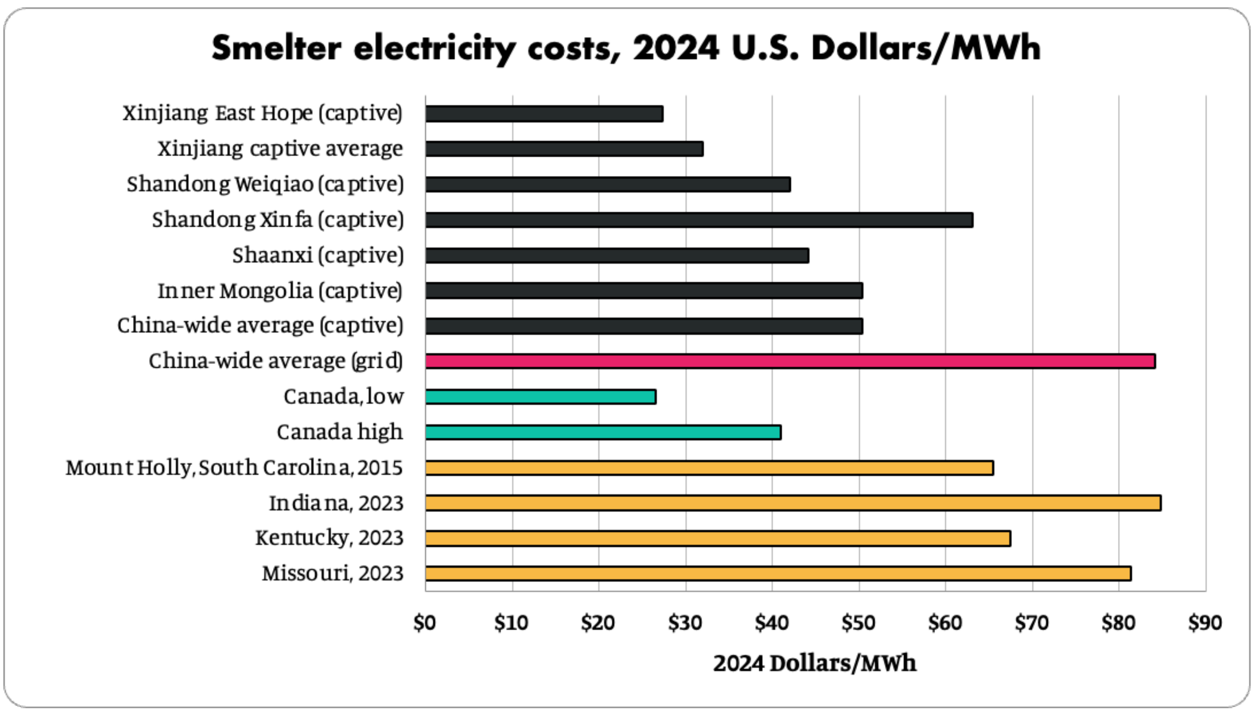

Figure 2: Comparison of aluminum smelter electricity costs between smelters in China and North America. Data for China and Mount Holly are from 2015 and 2016, respectively. Other U.S. and Canadian values taken from a 2025 Aluminum Association report. All Chinese electricity costs have been converted to U.S. dollars using the 2015 average exchange rate of 0.1592 CNY:USD. All electricity costs adjusted for inflation. Chinese captive coal power plant policies have evolved since 2015, so this figure illustrates energy cost fundamentals underlying the buildout of much of modern Chinese smelter capacity in operation today, as opposed to electricity prices attainable for new projects.

Chinese industry ranges between highly vertically-integrated industrial parks and dispersed facilities

- **Fewer attached anode furnaces and value-added casthouses.** In contrast to overseas smelters that possess onsite anode furnaces and attached casthouses that produce value-added products directly, some smelters in China operate independently, buying carbon anode blocks from dedicated anode providers like Sunstone and delivering only molten metal or crude foundry ingots (for-remelt) to customers focusing on product manufacturing.
- **Vast distributed downstream industry.** A large ecosystem of standalone casthouses and re-melt casthouses with fabrication plants operate throughout China, presiding either solely over the remelting of ingots sourced from smelters and casting of intermediate ingots and billets, or additionally the production of rolled or extruded aluminum parts.
- **Some vertically-integrated giants.** However, some large smelter complexes in China—generally facilities commissioned prior to 2015—exhibit a high degree of vertical integration with co-located upstream alumina powder production, carbon anode furnaces, and value-added casthouses. In most of these cases, alumina processing plants preceded the smelter. Such integrated industrial parks tend to belong to larger state-owned or state-affiliated aluminum groups like Chalco, Xinfa, and Hongqiao. Co-location of smelters with alumina processing plants is relatively unique to China.
- **Cheaper self-sourced alumina.** While alumina is typically a widely-traded commodity with comparable pricing globally, co-located vertical integration of alumina processing with aluminum smelting may give some firms an advantage by reducing the cost of alumina feedstock, typically the second-largest cost component of aluminum smelting after electricity costs.

Chinese facilities exhibit a considerable range of technological sophistication and scale

- **Good, better, best.** Smelters and casthouses in China span the full range in terms of modernity and scale of production capacity. Casthouses and fabrication plants in particular vary between smaller, labor-intensive workshop-style operations to large-scale, highly-mechanized factories with cutting-edge equipment. One expert described the contrast between an inland casthouse that required regular engagement to address degrading product quality every few months, versus a coastal fabrication plant more impressive than peer facilities overseas in their estimation: "China is the master of good, better, best."
- **Competitiveness through scale.** Higher-end facilities tap impressive economies of scale, with Chinese facilities installing say 25 extrusion presses relative to a typical U.S. fabrication plant that might operate two presses. Aluminum smelter complexes in China boast a high average nameplate capacity, and feature the largest plants in the world with many operating ten or more potlines in the same industrial park.
- **Digital coordination.** Several experts expressed admiration for the software integration in more sophisticated Chinese fabrication plants, yielding many efficiency improvements that they sought to document and share with company colleagues back home. They viewed such linked integration as both enabled by greater local access to engineering know-how and also necessary given the larger scale of these fabrication plants.
- **Some plants use more labor.** Some Chinese aluminum smelters and casthouses still rely on manual labor to higher degrees. One industry source described a small casting and extrusion plant that they worked with in 2023-2024 where female workers at workshop tables still bundled produced parts for shipment by hand. Video footage shows workers at some facilities still manually handling and bundling extrusion billets—using clearly hazardous practices in the case of one casthouse—and securing pallets of ingots with hand tools.

China's aluminum sector can build smelters quickly and at low capital cost due to several factors:

- **Build and repeat.** Chinese aluminum smelters leverage modular construction with minimal customization, drawing from the experience of previous projects and from on-site construction learning by building multiple potline buildings onsite in succession.

- **Different builder and operator responsibilities.** Experts emphasized the unique business structure of Chinese smelter construction, with a builder constructing the project to a turnkey standard then transferring the facility to the smelter operator with the operator responsible for commissioning and ramping up production. Simultaneously, the builder bears all responsibility for cost overruns, with no contingency fees.
- **Speedy local streamlining.** Industry veterans echoed the view that low-cost land, low-cost electricity, and fast-tracked regulatory approvals from provincial or local governments help dramatically accelerate project planning, minimize lead times, and reduce capital costs.
- **High speed and high risk.** Several experts expressed that Chinese industry emphasizes construction speed, often conducting construction 24/7, and in some cases accepts greater safety tradeoffs in exchange for speed. One recalled seeing workers without safety harnesses walking on beams 15 meters above the floor while installing a heavy extrusion press. Another was familiar with Chinese projects that would construct simultaneously at the roof level, on the operational floor, and at the basement level despite the risk of objects falling onto workers below.
- **Faster planned depreciation.** Multiple experts conveyed the view that Chinese companies plan for facility depreciation over timelines as short as 10 years, observing that plants did not seem built to last compared to overseas projects with a 30-year depreciation schedule. One expert expressed that this was a strategic choice given rapid recent progression in cell technology with a new standard emerging every several years.

Workers perform similar tasks, but their labor and safety experience differ

- **Labor is a small cost component.** Labor accounts for a minor percentage of smelter operating costs, with one expert suggesting a typical value of "less than 5%." Predictably, regions like China, India, and the Middle East enjoy lower labor costs, but this advantage is minor relative to factors like electricity costs and alumina prices. However, labor costs play a greater role in smelter project construction costs.
- **Potrooms are already labor-efficient.** Differences in automation across smelters appear to be minor. Aluminum production globally requires workers to conduct the same fundamental tasks, exposed to intense heat, dust, and hazards from molten metal, high voltage electricity, and industrial equipment. Some more modern smelters may marginally reduce workers on a potline with more mechanized anode-changing

equipment, but one expert impressed that even walking through an older potroom in the U.S., "you might see two to three people." But contrary to perceptions of Chinese "dark factories" that are practically fully-automated, human workers remain an integral part of potroom operations in China just as they do elsewhere in the world.

- **Chinese plants are equally or more labor-intensive.** Most experts consulted agreed that the Chinese aluminum sector likely still employs more people per ton of aluminum output than the aluminum industry in North America or Europe, although one source emphasized that the technology for further fabrication plant automation is widely available and extensively used in larger, modern Chinese facilities, but not all fabrication plants choose to adopt it. A coarse labor intensity comparison based on Chinese media and corporate reporting on particular projects suggests Chinese smelters are generally as labor-intensive or more labor-intensive than overseas facilities (Table 1).
- **Chinese labor hazards and abuse.** Multiple experts noted the contrast between Western workers who receive extensive training and certifications and Chinese workers brought in from the countryside immediately for on-the-job training on the facility floor. One source expressed that Chinese facilities prioritize production over safety, commenting that safety practices always involve a tradeoff against production. Another identified electrocution risks due to substandard grounding, insulation, and operating practices as a persistent issue. Several experts assessed Chinese safety practices and regulations as having clearly improved over time, particularly in wealthier provinces. Open-source research and United Nations investigations have highlighted forced labor risks at Xinjiang-based aluminum smelters that participate in state-sponsored labor transfer programs coercively targeting local Uyghur, Kazakh, and Kyrgyz peoples, prompting a number of countries to develop import restrictions on aluminum originating from Xinjiang.

Facility	Annual aluminum production capacity	Number of employees	Labor intensity (employees per ton nameplate)
Xinheng Group Qinghai Xingheng	675,000 tons/yr	3000	0.0044

Xinjiang East Hope Nonferrous Metals	800,000 tons/yr	3800	0.00475
Chalco Baotou Aluminum	1.3 million tons/yr	3246	0.0025
Yunnan Yunlu Runxin Gejiu	300,000 tons/yr	1000	0.0033
Yunnan Weiqiao Wenshan	2.03 to 2.89 million tons/yr	7220 to 12000	0.0025 to 0.0059
Xinfa Group Xinjiang Wujiaqu	1.35 million tons/yr	4000	0.0030
Yunnan Yunlu Zexin	250,000 tons/yr	880 to >1000	0.0035 to 0.004
Century Aluminum Mount Holly	230,000 tons/yr, 57,500 tons/yr currently idle, yielding a total of 172,500 tons/yr at present	465	0.0027
Century Aluminum Hawesville	250,000 tons/yr	628	0.0025
New Zealand Aluminium Smelters Tiwai Point	335000 tons/yr	670 to 1000	0.002 to 0.003
Rio Tinto Alma	473,000 tons/yr	810	0.0017
Alcoa Deschambalt Quebec	287,000 tons/yr	504	0.0018
Century Aluminum Sebree	210,000 tons/yr primary, 20,000 tons/yr secondary	625	0.003 (counting primary only) to 0.0027

Table 1: General comparison of labor intensity per unit of output between Chinese and ex-China aluminum smelters. Comparisons are inexact due to differences in facilities, particularly for Chinese facilities that may or may not include anode furnaces and value-added casthouses, whereas overseas smelters typically operate these supporting departments. It is also unclear whether employee totals for certain Chinese plants include coal power plant workers.

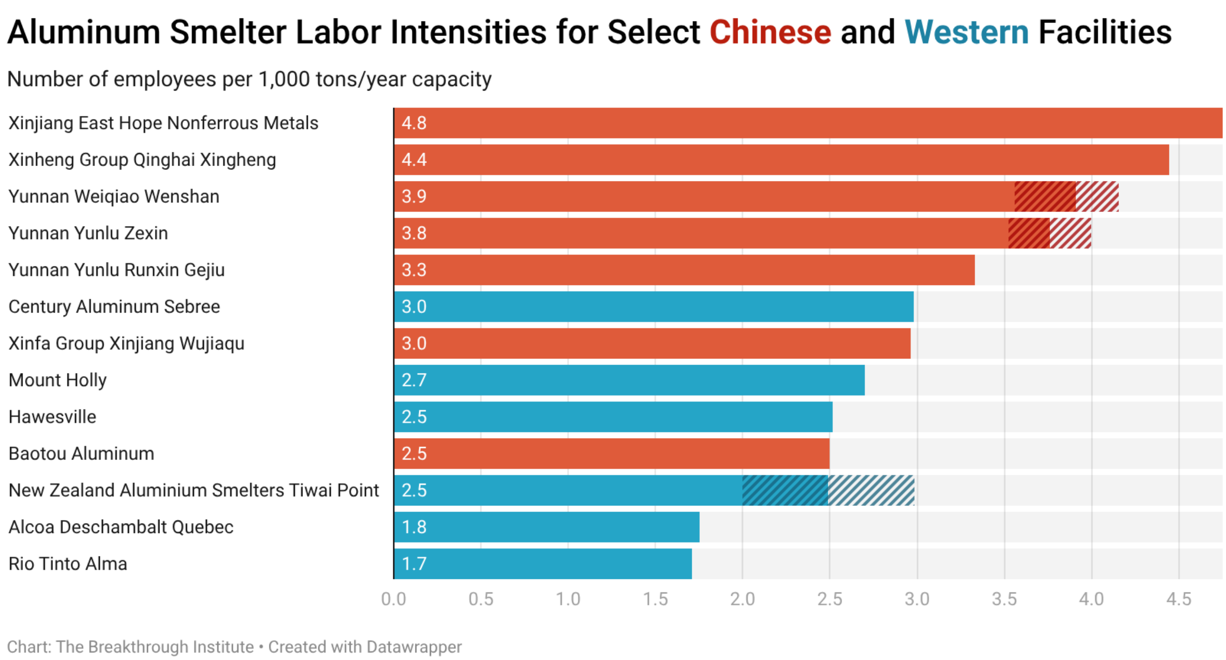

Figure 3: Estimated aluminum smelter labor intensity expressed as number of employees per 1,000 tons nameplate capacity. Hashed lines show a range of estimates for smelters where sources provided a range of production and/or employment.

Chinese industry is energy efficient but still produces largely emissions-intensive metal

- **Captive coal is still ubiquitous.** Most Chinese aluminum smelters make use of onsite captive coal-fired power plants, particularly new production in Xinjiang and Inner Mongolia but also much older production from the previous generation of smelter builds in the 2000s in provinces like Shandong, Henan, Gansu, and Shanxi. Aluminum production powered by onsite coal yields essentially the most carbon-intensive aluminum possible, while enjoying advantageously low effective electricity prices. Coal still generates ~75% of the electricity used to produce aluminum in China.

- **Higher-amperage pots.** Newer Chinese aluminum smelters do make use of more efficient, higher-amperage electrolytic cells in the 400kA to 600kA range that may reduce electricity consumption by up to 17.5% per ton relative to, say, 200kA cells used in older American smelters.
- **Race for limited hydropower.** The newest wave of aluminum smelter construction in China has seen an increased shift of smelter builds towards Yunnan and Sichuan powered by regional grid electricity, which is hydropower-rich with only 10-15% coal generation. Such new hydroelectricity-powered smelter projects should produce low-carbon aluminum only marginally more carbon-intensive than aluminum produced in regions like Norway, Iceland, or Quebec with fully clean power.
- **Inconsistent super greenhouse gas control.** One automatic technology with environmental relevance involves control systems installed at overseas smelters that automatically lower anode blocks deeper into the molten salt and aluminum bath to terminate a well-known "anode effect" reaction that emits perfluorocarbons (PFCs), an extremely potent greenhouse gas. Reporting from 2022 highlighted that many Chinese smelters have not yet installed such equipment and are continuing to rely on a far less efficient manual "stick method", with workers stirring the bath within cells to control PFC emissions.

Cutting-edge research in new smelter technology remains globally competitive

- **State-of-the-art equipment is narrow but international.** Rio Tinto, the Chinese institutes SAMI and NEUI, and the Russian corporation Rusal have respectively developed the highest-amperage (550 to >600kA) cell technologies, boasting a good balance between energy efficiency and aluminum output per pot per day.
- **Western firms lead on environmental efficiency.** Norsk Hydro and Rio Tinto are the world leaders in prototype cell technologies optimized for world-leading energy efficiency, with electricity consumption of <12,000 kWh per ton of aluminum, albeit currently with a tradeoff of lower aluminum output per pot per day. Norsk Hydro can arguably claim leadership in developing innovative digital twin controls to optimize the operation of its prototype cells. Through the startup venture Elysis, Alcoa and Rio Tinto are jointly developing a new inert anode technology to eliminate aluminum process CO2 emissions

via substitution of the carbon anode and are now testing a pilot 450kA cell, although Chinese institutes and Rusal are also working on inert anode concepts.

- **Chinese industry in wait-and-see mode?** One expert opined that the Chinese institutes SAMI, GAMI, and NEUI tend to respond to overseas technology efforts, moving rapidly to match new high-amperage standards rather than initiate advances themselves. Another characterized the Chinese institutes as innovative leaders but saw them as having deprioritized further technology development after reaching 600kA. Another disagreed, pointing out that Chinese industry has widely adopted 500kA and 600kA cell technology in new facilities over the past decade, whereas fewer plants in Europe and Canada have established or are establishing new production potlines with Rio Tinto AP60 600kA cells.

The U.S. possesses competitive recycling and fabrication, but smelters face challenges

- **Mounting smelter technical disadvantages.** U.S. smelters face dual challenges from relatively high electricity costs and aging, less-efficient cell technology and potline infrastructure. Currently-operating U.S. aluminum smelters were built between the years 1902 (Alcoa's Massena facility) and 1980 (Century Aluminum, Mt. Holly). In addition to consuming more electricity per unit of metal produced, older electrolytic cell equipment imposes higher maintenance costs.
- **A robust downstream aluminum sector.** However, most U.S. smelters have upgraded and maintained relatively more modern attached casthouses to produce value-added products, such as billets directly usable by fabricator plants. These value-added products have played a key role in enabling U.S. smelters to continue operating profitably. Meanwhile, a large landscape of fabrication plants operates throughout the U.S., up to and including state-of-the-art aerospace hot-rolling facilities that fabricate single-piece wing skins for jetliners.
- **Strong recycled production output.** The U.S. secondary aluminum recycling sector is also robust and has steadily grown over the past 40 years, reaching 3.3 million tons/yr of aluminum production in 2021 relative to a historic peak of 4.65 million tons/year of U.S. primary aluminum production in 1980.

4. How did China come to dominate the aluminum sector?

Phase Zero - Technical workforce development and long-term strategic planning.

Starting in the late 1970s, Chinese policymakers returned to the challenge of cultivating human capital to support development of China's minerals and metals sectors, long designated as strategic sectors. The first large cohorts of students entering universities following the Cultural Revolution received strong encouragement to focus on scientific and engineering disciplines and subsequently commenced work in state-owned industries. The national and provincial governments expand research institutes and engineering-focused universities tasked with advancing technical industry knowledge.

First phase - Initial growth and reform

Accelerating economic development supports growing demand for aluminum and other metals, supporting the expansion of both state-owned and newer groups of entrepreneurial private industrial firms. New facilities built in this era still lag considerably behind overseas facilities in technology and efficiency but help establish industry experience in plant construction and operation. During the 1990s, the privately-owned companies that would become some of the world's largest aluminum producers began expanding into aluminum production, with Hongqiao Group starting business as a textile manufacturer, Xinfa Group initially developing coal power plants, Huomei initially operating coal mines, and East Hope Group expanding across agriculture, chemicals, and coal power. The third major Chinese design, engineering, and research institute focusing on light metals, Northeastern University Engineering & Research Institute, forms in 1994 from Northeastern University's engineering department.

Second phase - Industrial policy for competitive globalization

By 2001 China becomes the world's largest global aluminum producer, producing 17% of world output in 2002. Chinalco is established as a state-owned aluminum corporation from several restructured state-owned aluminum companies. Around this time, amid Chinese accession to the World Trade Organization, Chinese policies aggressively support overseas export with tax rebates for exported production, coinciding with a surge in dumped Russian aluminum production that together largely halts overseas investment in new aluminum capacity. Meanwhile, both domestic and foreign investment starts to identify Chinese comparative advantages for siting new aluminum production, aided by favorable provincial and local incentives aiming to attract manufacturing investments.

Third phase - Capacity boom and economies of scale

From the mid 2000s to mid 2010s, a vast wave of new Chinese aluminum smelting and casting capacity rides heavily upon low-cost coal electricity, advantageous vertical integration with upstream alumina producers, and low capital costs for plant engineering and construction. Chinese policies seek to shut down and consolidate smaller plants into larger-scale facilities, using prescriptive potline technology standards to drive adoption of newer electrolytic cell models. China's minerals and metals industries generally push to acquire overseas assets and companies during and following the global financial crisis. For instance, Chinalco notably attempts to acquire a vast stake in Rio Tinto in 2009 for $19.5 billion.

Fourth phase - Consolidated process knowledge, tightening regulations

Tightening government energy and environmental policies reduce the aluminum sector's ability to take advantage of low-cost captive coal units for new plants, although occasional periods of permissive permitting allow some new captive coal projects to slip through. Policies slowly introduce scaling energy efficiency, pollutant emissions, and clean energy usage standards to ensure energy conservation and push older facilities into retiring or retrofitting. To limit overcapacity, policymakers have imposed a national 45 million tons/yr cap on aluminum smelter capacity since 2017, accelerating replacement of older, less-efficient plants by more modern plants with many facilities taking advantage of hydropower in provinces like Yunnan, Guizhou, and Guangxi. While regulations no longer allow new low-cost, dirty production going forward, Chinese industry expertise enables fast and affordable construction of new plants, keeping new builds economic amid rising operating costs.

Many trends associated above with particular phases could arguably trace their origins to developments that commenced during earlier phases, and the boundaries between the described phases are ultimately subjective. All in all, this timeline seeks to provide only a generalized narrative of the history of China's primary aluminum sector for the sake of context.

5. What steps can assure a more competitive light metals sector outside of China?

In reevaluating its strategy for the light metals sector, the United States or Europe is hardly prioritizing a determined march to 25% let alone 50% of global aluminum production per se, but rather two goals. The first straightforward goal is to better address strategic vulnerabilities in light metals. The second broader goal is to foster an ecosystem that again enables new investment in electricity-intensive heavy industries. Pursuit of both goals requires multi-pronged strategy to rebuild process knowledge, compete in innovation, and reduce import dependence, while strengthening versatility throughout the light metals sector by leveraging magnesium alongside aluminum and both recycled and primary feedstocks.

Older existing aluminum smelters need upgrades to ensure longevity

- **Battling against the clock.** American aluminum smelters are aging, as are counterparts in Europe, Canada, Oceania, and South America. Companies and workers have devoted admirable effort into facility upgrades and efficiency improvements where possible, but everyone from the potroom foreman to the executive suite knows that their smelter and others of similar vintage eventually face major decisions over upgrading major equipment.
- **Retrofits are needed but not easy.** Such upgrades would require high upfront costs but provide important long-term benefits. With potroom buildings designed specifically to house the electrolytic cells that produce molten aluminum, installation of newer and larger modern cells would require completely rebuilding the buildings themselves. But carrying on with existing equipment now reaching 30 to 50 years of age demands more electricity consumption per unit of metal, higher maintenance costs, and continued operational inefficiencies.
- **Sizable gains via upgrades.** Relative to older 170kA to 228kA cells such as those installed in the Rio Tinto Grande Baie smelter or Century Aluminum's Mount Holly smelter, a newer set of AP60 kA cells would reduce electricity use from 15,000 to as low as 12,850 kWh per ton, an improvement of 14.3%. With the cost of electricity typically making up 30-40% of the production cost of fresh primary aluminum, such upgrades represent total savings on

the order of 5.75%. In addition to reducing energy and maintenance costs, newer electrolytic cells and overhead crane equipment increase production efficiency, accelerating processes like the collection of produced aluminum or the replacement of anode blocks.

Tariffs will not save American primary aluminum long-term

- **A missing long-term strategy.** Indiscriminately protecting American aluminum via blanket tariffs only procrastinates eventual moments of reckoning with smelter equipment age without offering any longer-term strategy, merely delaying the ongoing shift of U.S. industry towards secondary recycled production. What the U.S. aluminum sector needs is decisive investment and policy support to future-proof facilities with state-of-the-art new technology.
- **Shifting trade winds don't bring investment.** Particularly given future trade policy uncertainty, tariff protections today do nothing to resolve compounding fixed plant infrastructure inefficiencies, strengthen U.S. industry process knowledge, or provide sufficient long-term certainty to justify new investment in U.S. primary aluminum—which also competes with robust domestic recycled aluminum production.
- **Tariffs on partners raise problems.** Blanket tariffs—including on aluminum traded from Canada, Europe, and South America—also complicate potential U.S. investment and technical collaboration by international firms like Rio Tinto and Norsk Hydro, while merely adding operational costs to complex North American supply chains that have long relied on unobstructed trade of metal and fabricated parts back and forth with Canada in particular. A sustainable US strategic metals strategy ultimately depends on allied scale.
- **Focus trade policy on China.** However, U.S. policymakers possess a strong case for maintaining the tariffs on Chinese aluminum, to insulate U.S. producers from the strong market effects that can manifest due to Chinese policy changes. For instance, China's large aluminum stockpiles mean the Chinese government still maintains some capability to flood aluminum markets despite national caps on production capacity. U.S. policymakers should work with international allies and partners to harmonize trade policies in ways that provide collective insulation from market volatility.

Low-cost electricity is key for new investment in electricity-intensive heavy industry

- **Again, investment requires cheap power.** Multiple experts agreed that assured, affordable long-term power prices typically underpin decisions about investing in new projects or significantly retrofitting operating facilities. A recent Aluminum Association white paper suggests new projects and retrofits require 20-year and 10-year power contracts at or below $40/MWh, respectively.
- **Aluminum is just one electricity-intensive heavy industry.** Affordable industrial electricity rates provide a foundation not only for the aluminum industry but also other electricity-intensive heavy industries like polysilicon refining, semiconductor ingot growth and wafer slicing, steelmaking via molten oxide electrolysis, and synthetic graphite production. No country has established major aluminum production without significant state support to assure provision of affordable electricity.
- **Public power for production.** Policymakers must explore programs that guarantee low electricity prices as a matter of firm government support to such electricity-intensive critical mineral and manufacturing activities. The New York Power Authority's Preservation Power program, which allocates 490 MW of output from the St. Lawrence Franklin D. Roosevelt Power Project at favorable rates to businesses that make new investments in three counties of upstate New York, may provide a useful model for federally-owned public power agencies like the Tennessee Valley Authority and Bonneville Power Administration.

Pursuit of environmental efficiency will aid technological competitiveness

- **Inert anode demonstration.** Pursuit of "inert anode" technologies can not only eliminate incidental CO2 and pollutant emissions from the consumption of carbon anodes in the molten bath, but could also streamline smelter operations which must currently produce, store, prepare, insert, and change anodes constantly during aluminum production. At the same time, advances in anode technology for electrolysis may also benefit other industrial processes such as steelmaking. However, potentially exotic or expensive inert anode materials may pose their own cost and supply challenges. The prototype Elysis inert anode cells rearrange the anode and cell configuration vertically rather than horizontally to extend anode life, thus increasing the likelihood that significant retrofits, rebuilds, or new plants may be required to adopt inert anode technology.

- **Carbon capture.** Research and development of carbon capture technology to strip CO2 from aluminum smelter flue gas streams may not only benefit efforts to decarbonize primary aluminum production but also other industrial processes like metallurgical silicon smelting or cement production. However, the cost and energy consumption associated with operating carbon capture equipment present continued difficulties, especially because of the low carbon dioxide content of smelter flue gas.
- **Advanced digital operation.** Improved control of the electrolytic process within the cell can both mitigate the issue of PFC emissions from certain isolated zones within the bath, while also improving the efficiency of electrolytic cell operation and helping drive advances in modeling and control. Such efforts can benefit other techniques such as molten salt electrolysis in rare earths processing, which similarly emits significant PFCs.
- **Efficient electricity consumption.** Improved specific electricity consumption per unit of aluminum produced obviously helps reduce production costs and minimize the level of onsite electricity infrastructure needed to support a given level of production. In general, efforts to reduce electricity consumption and maximally leverage clean electricity inputs will help keep aluminum production competitive particularly in the face of fee-based trade adjustments correcting for the metal's environmental footprint, such as the EU's border carbon adjustment policy.
- **Variable current tolerance.** Some Chinese laboratory testing has explored development of new types of aluminum electrolytic cells with adjustable waste heat recovery systems that can operate under greater power fluctuation, possibly enabling aluminum smelters to more easily use variable renewable electricity generation. Small-scale pilot tests and modeling suggest a potential to design cells capable of withstanding current fluctuations on the order of 20%, but efforts to adapt such technology commercially do not appear to have progressed.
- **Alternative aluminum sources.** Some technology research and startup efforts are exploring alternative pathways to source alumina from minerals other than bauxite, such as quarried calcium silicate, potentially allowing for production of alumina as a byproduct of alternative cement production.
- **Secondary metal alongside primary metal.** Continued efforts to expand production of recycled aluminum and collection rates for post-consumer aluminum scrap can help maintain existing competitive strengths in the secondary recycled aluminum market. At the same time, a continued policy focus on primary aluminum remains valuable in light

of the persistent need for high-purity aluminum, expected growth in total global aluminum demand, and the strategic value of cultivating process knowledge in electricity-intensive electrolytic industries.

Electrolytic magnesium production can substitute for aluminum in many light metal applications

- **Why magnesium?** Magnesium metal can replace aluminum metal in numerous aerospace, automotive, and general consumer and structural applications, with the advantage of added weight saving relative to aluminum. While China currently dominates global magnesium production using the carbon-intensive and labor-intensive Pidgeon process, a number of companies globally are striving to optimize and reintroduce the electrolytic production of magnesium metal using naturally-occurring salts isolated from seawater.
- **Essential industrial ingredient.** At the same time, magnesium serves as a key input for other important industrial processes including steelmaking, titanium production, beryllium, amorphous boron, hafnium, zirconium, aluminum alloys, and potentially ultrapure silicon.
- **Opportunity to outflank.** Pursuit of electrolytic magnesium metal production from seawater can produce outsized strategic benefits for regions like North America and Europe, given the less established and more globally contested landscape for technology leadership for this relatively less mature approach.
- **A limited window to take the lead.** As evidenced by the very naming of the SAMI and GAMI metallurgical research institutes, however, China has long recognized the technological and strategic connections between aluminum and magnesium and efforts in China to progress electrolytic magnesium techniques are advancing. Other countries should act decisively to avoid falling behind in this sector.

Policies must distinguish electricity-intensive heavy industry from data center loads

- **Electricity-intensive metals compete with data centers.** The policy impulse to ensure that rapid data center construction by companies with a high willingness to pay for electricity does not impose unfair electric bill increases upon ratepayers is correct, but lawmakers and regulators should exercise care to treat industries like aluminum or polysilicon distinctly from data centers.

- **Metals bring jobs and industrial knowledge.** AI hyperscalers and tech companies often exhibit a far higher willingness to pay for electricity, yet data centers may not provide the same strategic industrial base capabilities that a broader array of manufacturing investments might, and similarly create less employment and fewer high-quality jobs per gigawatt of electricity consumption while competing for the same baseload electricity.
- **Important opportunities for synergy.** On the other hand, accelerating data center construction may drive useful regional planning and industry experience-building that ultimately aids in the siting of large power-hungry industrial sites, while also creating data center sites that might ultimately retire and allow heavy industry to take over the grid interconnection location.

The United States must pursue additional pathways to produce high-purity aluminum

- **Constricted high-purity supply.** The curtailment of Century Aluminum's Hawesville smelter in 2022 has shuttered the largest domestic producer of high-purity aluminum (HPA) of grades between P0406 and P0202, in other words containing less than 0.4% silicon and 0.6% iron, as opposed to standard P1020 aluminum. Consequently, the United States faces greater risks from import dependence on HPA, which contains fewer potential failure points and boasts greater strength for aerospace, defense, and other specialty applications.
- **Future HPA production needs a new path.** While a valuable asset, the Hawesville smelter may not offer a long-term or large-scale solution for HPA supply security, as Hawesville's production of HPA partly results from its use of older smelter equipment that does not capture flue gases in the incoming alumina stream (dry alumina injection scrubber), a standard emissions control technique that also introduces some impurities. Hawesville's currently uncertain future aside, any significant upgrade to the Hawesville cell technology would likely mean the smelter would no longer produce HPA under regular operation.
- **Purity through meticulous operation.** However, careful and precise operation of electrolytic cells at existing smelters—more frequent tapping of molten alumina from each pot and more regular carbon anode block replacement, followed by filtration of tapped molten metal—can yield HPA. Other smelters globally such as Rio Tinto's New Zealand smelter and Emirates Global Aluminum's Jebel Ali smelter perform this practice

for certain pots reserved for HPA production. Use of alumina feedstock and carbon anodes with minimal impurities greatly facilitates such operations but adds cost.

- **High-purity upgrading.** A number of processes can upgrade standard primary aluminum to HPA. Arconic, a major defense and aerospace manufacturer, produces high-purity aluminum for internal use by upgrading standard-grade aluminum ingots via the R214 process which employs fractional crystallization. The Department of Defense issued a Defense Production Act Title III grant to Arconic in mid-2023 to increase this production capacity. The oldest high-purity upgrading process, the Hoopes process using three-layer electrolysis, has been known since the 1920s and has undergone improvements but requires even more electricity per kilogram of HPA (17-18 kWh) than the typical smelting of aluminum itself (12 to 15 kWh). Besides the United States, Russia, and China, several Japanese producers and some of Norsk Hydro's European operations possess relevant expertise in high-purity upgrading.
- **Research high-purity recycled production.** Recycled aluminum typically contains more impurities than new primary metal, increasing the challenges associated with secondary purification. However, efforts have continued to develop techniques to economically produce HPA from post-consumer scrap.

To establish new facilities competitively, industry must strengthen management of large capital projects

- **Western project structures are cost-heavy.** Outside of China, large aluminum projects often employ external engineering consultancies to act as project managers who in turn hire subcontractors to perform specific tasks like construction and equipment installation. The engineering firm often collects a fee on the order of 20% of the project capital cost, while also stipulating contingency fees to cover unforeseen project costs.
- **Shifting industry culture.** One expert expressed that a more competitive primary aluminum sector in North America, Europe, and elsewhere would require a progressive shift towards greater discipline, with the builder taking on greater responsibility for contingencies and schedule overrun.
- **Incentivizing EPC performance.** Structuring engineering, procurement, and construction (EPC) contracts with award fees for achieving project milestones on-time and on-budget could help align project management firm incentives with efficient performance, but

requires clear and strict milestone criteria. In any case, an award fee system may itself add further cost and does not necessarily shift greater risk sharing onto the EPC firm.

Light metals sector diversification and sustainability requires policies to level the environmental and labor playing field.

- **Pressuring Chinese coal-fired metal.** While the Chinese aluminum industry is introducing more renewable electricity inputs and relocating some production to hydro-rich provinces, the sector is arguably bifurcating between captive-coal-based and hydropower-based production, with central government policies balancing improved environmental efficiency carefully with economic interests. Recognizing these dynamics, overseas policymakers should act to ensure that coal-based, socially-problematic production in China faces the greatest pressure to reform or retire.
- **Excluding Xinjiang aluminum with forced labor risk.** About 15.7% of Chinese aluminum (~10% of global production) continues to originate from industrial parks in the Xinjiang Uyghur Autonomous Region that are exposed to multiple vectors of forced labor risk—from coal mining to construction to local coal power generation to the aluminum companies themselves. Overseas governments should expand trade restrictions against products containing Xinjiang-produced aluminum unless affected companies can provide clear and convincing evidence that the aluminum was not produced using forced labor.
- **Promote high supply chain standards.** Policymakers should generally support the development of international labor and environmental certification-based standards, such as the Consolidated Mining Standard Initiative (CMSI), and strive to enact policies and negotiate binding international agreements to extend such certification and accountability frameworks to as much of global production as possible. Such efforts should particularly extend to upstream bauxite mining and alumina processing, which carry elevated pollution risks from surface mining and handling of bauxite residue wastes.

6. Conclusions

This deep look at the aluminum sector highlights that arguably, the Biden-Trump U.S. policy consensus has not been wrong to fight to protect the future of aluminum smelting in the United

States. A healthy primary aluminum industry confers valuable strategic capabilities beyond the immediate value of the metal produced—capabilities that have atrophied in the U.S. and that can be re-learned only through fresh practice. However, a tariffs-centric approach is both flawed and incomplete, as tariffs do not address the deeper factors needed to catalyze new industrial infrastructure investments that truly build technical mastery and sectoral strength.

The insight that aluminum provides for broader reindustrialization efforts—perhaps not only in the U.S. but also for other regions like Europe—is that the process is as important as the product. A business environment that allows new large-scale primary aluminum projects to move forward is one where industrial electricity and raw material inputs are affordable, where expertise and turnkey equipment are widely available, where regulations and business culture allow high capital cost projects to move forward quickly, where the market perceives certainty of demand, and where the sector can achieve large economies of scale. At the same time, an industrial ecosystem that can produce aluminum skillfully also possesses the characteristics to successfully produce magnesium, polysilicon, synthetic graphite, rare earth metals, copper, steel, and more.

The future of industrial competitiveness in strategic metals and materials differs in some key ways from the future of industrial competitiveness in smartphone or automobile manufacturing. Aluminum and iPhones are different. For aluminum of a given quality specification, one ton of metal is one ton of metal. Unlike consumer electronics differentiated by their capabilities, a customer possesses no intrinsic incentive to buy a ton of metal with the higher price tag.

The challenge the world now faces across the full range of critical materials and metals is that China achieved dominance in these sectors with the help of a heavily polluting, low-cost industrial ecosystem that has held back broader progress on alternative, cleaner approaches to produce these commodities. Certainly from an environmental perspective, the massive fleet of Chinese smelters fed with power from onsite coal plants is not particularly innovative and possesses no long-term technological future. Yet at the same time, China will hardly rest on its laurels. Such massive economies of scale have established genuine know-how and technological competency that give the country a head start towards the development of next-generation techniques that could ensure China dominates not just the present but the future of many strategic industries.

If policymakers really see such commodities and industrial capabilities as strategically vital, then the best plan of action depends on establishing the conditions necessary for retrofitting and building new projects at ambitiously large scale. Such a strategy must assure affordable industrial electricity, de-risk large capital cost project development, and coordinate broader global restrictions on goods produced with poor environmental and labor practices, while competing to develop and commercialize next-generation, future-proof technologies.