Accepted Manuscript

Geoenergy

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DOI: https://doi.org/10.1144/geoenergy2023-054

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Received 19 December 2023
Revised 8 May 2024
Accepted 17 May 2024

Compound criticality of bauxite production: implications for sustainability and trade neo-colonialism.

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Abstract

We describe bauxite as having compound criticality. 1, it is a critical raw material (CRM) from which alumina and thereby aluminium are produced, and aluminium has the highest production levels of all metals deemed significant to the Clean Energy Transition. 2, gallium is a by-product CRM, extracted during alumina refining. 3, multiple other CRM by-products could be extracted during alumina refining: scandium, lithium, cobalt, titanium and REE. 4, production is profoundly influenced by price inelasticity (for by-products), regime instability of bauxite production and supply chain bottlenecks. We review the geology of bauxite ore deposits as a function of complex CRM supply potential, and interrogate the trait of criticality using four of the world's dominant producer nations of bauxite and potential patterns of value addition from raw materials to refined products. Trade agreements and mitigation strategies to ensure security of supply in consumer regions prioritise removal of low-cost bauxite by large-scale mining operations and shipping of unprocessed ore at high CO_2 footprint from producer nations. Ore-refining nations have investments that are deemed extractive because they remove large quantities of raw material for export with minimal or no in-country processing and they can also place producer nations in debt. Opposition to neo-colonial debt-trap policies and extractive practices increases regime instability and thereby criticality. We highlight how societal-environmental-political interactions and the mineral-energy nexus in the bauxite-aluminium supply chain are subject to increasing turbulence, which may reshape the geographies of supply chains.

Introduction

Bauxite is the ore for the bulk metal aluminium. The World Bank identified aluminium as the 'high-impact, cross-cutting metal' that has the highest production levels compared to all other metals deemed significant to the Clean Energy Transition, with cumulative production reaching 102 million tons by 2050 to primarily supply solar PV and then other energy technologies (Hund *et al.* 2022). Demand for primary aluminium is forecasted to increase by 50% to 2050 globally compared to 2017, and transport is expected to drive 55% of growth in demand for semi-finished aluminium from 2017 to 2050 (European Commission 2020a). The use of aluminium in green energy technologies - and for light-weighting the transport fleet - arises from its characteristic properties. These include remarkably high strength to weight ratio (that can be increased further by its excellent alloying potential), conduction of heat and electricity, low melting point, malleability, and corrosion resistance.

Critical raw materials (CRMs) are described as of manufacturing, economic, and/or national strategic importance, with supply chains that are determined to be at significant risk of short supply. Definitions and designations of criticality vary by geographical region or nation, industrial sector or individual company (Bobba *et al.* 2020; Lusty *et al.* 2021; Nassar and Fortier 2021; European Commission 2023). Analysis of criticality also changes over time. The European Commission (2023) assessment of criticality combines bauxite and aluminium for consistency reasons but figure 1a depicts the criticality of bauxite and aluminium separately, following the European Union assessment of 2020, in order to gauge vulnerability in the supply chain. The value of the world production of bauxite in 2016 was estimated at EUR 12.7 billion, and of primary aluminium was EUR 86 billion (European Commission 2020a). The reliance of the EU on bauxite and primary aluminium imports was 87% and 59%, respectively, between 2012 and 2016 (European Commission 2020a) and while both commodities are viewed as economically important, only bauxite (European Commission 2020b) was identified as a critical raw material in 2020 (Figure 1a). In 2023, combined bauxite/aluminium raw materials are designated as CRM (European Commission 2023). A European concern about import dependence is amplified by concerns about considerable risk to responsible sourcing that arise from weak governance in Guinea, which is the main source for the EU supply of bauxite (Georgitzikis *et al.* 2021). The EU mine production of bauxite in 2021 was 0.4% of global production, at under 1.4 million tonnes, and 89% of EU production was in Greece (data derived from World Mineral Statistics, British Geological Survey 2023). In contrast, EU alumina production of 5.8 million tons per year, has been 5% of the global total (Georgitzikis *et al.* 2021). Ireland (30%) and Spain (25%) produce more than half of EU alumina (Georgitzikis *et al.* 2021).

Pure aluminium is fully reusable and recyclable an infinite number of times, but the practical rate of recycling of end-of-life scrap aluminium is significantly lower (42-70%, up to 90% in some countries; (Hund *et al.* 2022). The availability of scrap aluminium is not enough to meet demand so the rate of use of recycled aluminium is only 34-36% (Hund et al. 2022a). In the unlikely (due to material losses and potentially sub-optimal performance of recycled materials) event that aluminium recycling can reach 100%, projected increases in demand for aluminium indicate that the maximum theoretical contribution of recycled aluminium to 2050 global demand is 61% (Figure 1b; Hund et al. 2022). The drive to recycle aluminium is not merely a response to increasing demand but also part of the EU strategy to reduce energy intensity of the aluminium industry. The carbon footprint of aluminium production in Europe declined by 84% from 1990 to 2018 in response to: (1) a decline in primary production and increase in secondary production, which has 5% of the energy intensity of primary production; (2) a reduction in the energy intensity per unit of primary production from 15 t CO_2 eq/t (2015) to 6.8 t CO_2 eq/t (Georgitzikis *et al.* 2021; IAI 2023). The global aluminium sector produces 1.1 billion metric tons of CO_2 emissions per year (roughly 3% of global emissions) at a global average of 16.1 t CO_2 eq/t, which is more than seven times higher than the emissions associated with production of 1 t of steel (European Commission 2020a; Georgitzikis *et al.* 2021; IAI 2023).

The importance of bauxite deposits is not constrained to the aluminium supply chain. Gallium is an example of a critical raw material that is extracted exclusively as a by-product of a bulk metal ore, i.e. bauxite (aluminium) or sphalerite (zinc) ore (Butcher and Brown 2014). The concentration of gallium is highest in bauxite deposits formed above alkali source rocks by intense weathering, such that geological controls underpin the potential for additional value generation from the bauxite-aluminium value chain. Gallium is used in electronics and photovoltaic applications. Bauxite is an important host of numerous additional technology metals that are deemed of economic significance or at risk of supply shortage to the European Union (Figure 1a, 1c). The chemical composition of bauxite deposits (e.g. Herrington et al. 2016) reveals that the CRMs and strategic metals that are not currently produced as by-products are scandium and REE, lithium, cobalt, titanium, vanadium, nickel, chromium and zirconium. The technological applications of potential by-products include photovoltaic cells, batteries and permanent (Nd) magnets as well as alloying for steel. Most of the potential by-product metals are mined as the primary commodity of interest in other types of ore deposits (e.g. REE; Goodenough et al. 2016), but recovery of by-product might be an approach to diversify access to raw materials. The potential for security of supply to be increased is hampered by low critical co- and byproduct resource reporting that results from perceived or actual low monetary value of by-products at the mine site rather than as a result of any lack of these metals (Mudd *et al.* 2017).

The aluminium supply chain can be used to highlight the significant influence that the Resource Curse has on the modern-day mining industry. We use the (Ross 2015) definition of the Resource Curse: the inability of resource-rich countries to unlock the benefit of natural resources for the social, economic and political growth of countries, instead these countries are impacted by negative legacies that proliferate as a consequence. The exploitation of countries with poor-governance with large bauxite reserves is often the continuation of colonialist approaches adopted by former colonial powers, sometimes known as neo-colonialism (Lassou *et al.* 2019; Odijie 2022). Whilst new investors including China and the United Arab Emirates have no colonial ties in Africa, the extractivist nature of their investments also promotes neo-colonialism and some cite China as the new face of neo-colonialism in Africa (Carvalho and Doherty 2013; Agbleke 2018). Despite the possession of large bauxite reserves rarely do countries, such as the bauxite-endowed nation of Guinea, see the expansion of their domestic mining industry to processing of a higher-value product (alumina refining), so the mining chain cannot retain value. Both foreign investors and consumer countries see a cost-benefit from disorder and weak governance in Guinea, such that it is used as one of four case studies in this manuscript, being compared to other consumer and producer countries (India, Australia and China) to determine worldwide trends.

In this manuscript, we investigate the nexus between the geology and geography of bauxite deposits, and the socio-political and historical relations that influence regime stability and supply risk. The quantitative data that is analysed includes statistics for production, imports and exports in the global bauxite to primary aluminium (does not include recycled aluminium) supply chains, and indicators for wealth and prosperity (European Commission 2020a, b, 2023; Georgitzikis *et al.* 2021; British Geological Survey 2023; United Nations 2023a, b; World Bank Group 2023b, a). Micropolitical contexts and social sustainability perspectives are based on quantitative data (World Bank, accessed 2022), combined with expert and qualitative testimonial data gathered in the field and from literature (Diallo 2019, unpublished data from field activities of Diallo 2020-2023, and News articles). From our analysis, we examine how modern framings and mitigation strategies for critical raw materials combine with colonial legacies and neo-colonial approaches to perpetuate the Resource Curse. We aim to extend technical dialogues that describe the challenges to progress, and to highlight the linkages between geology and social sustainability for critical raw materials.

Occurrence of bauxite deposits

Herrington et al. (2016) provide an overview of the occurrence of bauxite, describing its formation by residual enrichment of the least mobile components of weathering alumina-silicate rocks, in climatic conditions with annual precipitation higher than 1.2 m and mean annual temperature > 22 °C. Bauxites therefore form in tropical and sub-tropical climates (e.g. South America and western

Africa), particularly on ancient Gondwana platforms in tectonically stable shields (Bogatyrev and Zhukov 2009). Palaeo-bauxites formed in tropical-subtropical climates during and/or by the late Cretaceous are now located in temperate Mediterranean climates such as in Western Australia and the Tethys region (Herrington *et al.* 2016). There is a fairly widespread global distribution of ore deposits so that bauxite mining occurs on all continents (Figure 2). The largest bauxite reserves are in Guinea (7400 million metric tonnes), Vietnam (5800 mt), Australia (5300 mt), Brazil (2700 mt), Jamaica (2000 mt), Indonesia (1200 mt), China (1000 million tonnes), India (660 mt) and Russia (500 mt) (USGS data via Statistica, 2022).

There is a three-fold, largely genetic, classification of deposits into lateritic bauxite, karst bauxite and Tikhvin-type (Bárdossy 1982). The types reflect the bauxite-basement relationship, as a proxy for the extent of remobilisation and transport of material, as follows. Whereas karstic bauxites (e.g. Figure 3a) infill solution cavities, and Tikhvin-type deposits have no genetic relation to the aluminosilicate rocks beneath them, lateritic bauxites dominate global reserves and are located *in-situ* above the weathering protolith (e.g. Figure 3b-d) (Deady *et al.* 2016). Due to the superficial nature of all the deposit types and their geologically recent origin (usually mid-Cretaceous to mid-Tertiary), most are within 1-2 m of the surface, with a common thickness between 3 and 15 m (Donoghue *et al.* 2014).

The classification of bauxite deposits is modified to sediment-type, accumulation-type and lateritic type for Chinese deposits, which arise from palaeo-weathering (Sun *et al.* 2020). The deposits may be located in geosynclines, and ore bodies may be laterally discontinuous, complex or irregular shapes. Prediction models have been used to assess the potential for Chinese ore deposits up to a depth of 1000 m, suggesting that there is a huge reservoir of undiscovered bauxite deposits (Sun *et al.* 2020). However, buried ore deposits are unlikely to be economically competitive with shallow deposits with easy access (Figure 3e). Economic reserves in China are limited by the depth and relatively low grade of deposits so that bauxite, alumina and aluminium-based industries are reliant on imports from other producing nations (Pan *et al.* 2019). Sedimentary and lateritic bauxite ores above Ordovician and Silurian formations of the West African Craton are located in the major producing region of the Balaya bauxite plateau in the Kindia bauxite province of Guinea (Sidibe and Yalcin 2019). Gibbsite [$Al(OH)_3$], goethite [FeO(OH)], and aluminous goethite [(Fe,AlO(OH)] are the major mineral components; anatase, rutile, diaspore and kaolinite are minor minerals, with zircon and clastic quartz as accessory minerals in the bauxites, and Sidibe and Yalcin (2019a) cite whole rock chemistry: 49.70–61.00 wt% Al_2O_3, 0.30-5.00 wt% SiO_2, 1.60-19.00 wt% Fe_2O_3, 1.71–3.70 wt% TiO_2.

Immobile high field strength elements (HFSEs) are Ga, Sc, total rare earth elements (REE) and TiO_2 that reach concentrations of 100 ppm, 75 ppm, 1100 ppm and 5 wt %, respectively (Figure 4) in both karstic bauxites in Europe and in lateritic bauxites in west Africa (Herrington *et al.* 2016; Sidibe and Yalcin 2019). The variable concentration and dispersion patterns of trace elements in bauxite (Figure 1c) is a function of the nature of the original protolith and the duration and intensity of the bauxitisation (i.e. the largely weathering that forms a lateritic bauxite deposit, as described above) process (Boski and Herbosch 1990). Sidibe and Yalcin (2019) determined that Ti-bearing minerals are the carrier for the trace elements HREE, HFSE, Sn, U, Ga, W and Y; and that Fe-bearing minerals are the carrier for the trace elements Mo, Cu, Pb, As, Sb and Bi. Hydrogeological (e.g. water table) conditions and physical (e.g. fragmentation) conditions are emphasized for chemical redistribution across bauxite-bearing lateritic profiles (Taylor and Eggleton 2008; Makarova *et al.* 2019; Mamedov *et al.* 2019).

Processing and production of bauxite and its derivative products

Bauxite typically contains around 55 wt % Al_2O_3 in the minerals gibbsite, which dominates modern lateritic bauxite deposits of tropical and sub-tropical climates, and the less hydrous boehmite [γ-AlO(OH)] and diaspore [α-AlO(OH)] that are more common in mature (fossil) lateritic and karst bauxites such as in the Tethys region (Herrington *et al.* 2016). Figure 4 shows that process of metal recovery from bauxite ore. Rocks are crushed, sorted and washed, and then undergo beneficiation before transportation. The transportation of bauxite as dry or wet slurry changes the weight of ore and thereby both the cost of transportation and the carbon footprint (e.g. Rajkovic et al. 2016), as well as the potential for liquefaction risk during transport (Wu 2020). However, the carbon footprint and hazards of transportation do not dictate where the ore is processed: the global distributions of alumina and aluminium production centres are not always located proximal to major centres of bauxite production (Figure 2).

Approximately 90% of bauxite mined in the world is converted to alumina (aluminium oxide) using the Bayer process (Georgitzikis *et al.* 2021). The Bayer process removes excess water from aluminium trihydrate [$Al(OH)_3$], i.e. gibbsite, by addition of caustic soda (NaOH). The resultant sodium aluminate ($NaAlO_2$) solution is separated (figure 4) from red muds, the bauxite residue. Detailed knowledge of the different ore types and their mineralogical compositions is important for both the main and potential by-products of bauxite. For example, lateritic bauxites of the Fria district in Guinea, with a schist protolith, have 9% of the total Al_2O_3 in insoluble pyrophyllite that cannot be recovered by leaching in the Bayer process and solution of kaolinite decreases efficiency through scale formation (Boulangé *et al.* 1996). In the general case, by-products Ga (and potentially Li) can be extracted from the sodium aluminate solution, while the potential by-products Sc, Ti, Fe and REE (from minerals associated with the ore including anatase, hematite, goethite) partition into the red mud waste along with residual Al and Ga. Research using a combined hydro-pyro flowsheet involving carbonation – HCl leaching – $C_2H_2O_4$ leaching – H_2SO_4 baking – water leaching process suggests that there is considerable potential for enhanced recovery from red mud (Agrawal and Dhawan 2022).

The variable concentration of potential by-products (Figure 1c) in the primary ore depends upon lithological contexts and the mode of formation of bauxite. REE, for example, have higher concentration in alkaline igneous protoliths (Goodenough *et al.* 2016). Regardless of protolith, REE can be concentrated towards limestone substrates that act as a geochemical barrier to REE in solution. The REE are therefore ideally concentrated in karst bauxites and further concentrated during the alumina production process: (Deady *et al.* 2016) calculated that ~12,000 tonnes of REE exist in red mud waste at just two case study areas in Greece and Turkey. Unit processes by which various by-products have been extracted from red muds include: smelting-leaching processes for Ti, Al and REEs; acid leaching (or carbonate leaching for Sc), hydrolysis, or solvent extraction for REE; multiple NaOH and acid leaching steps with hydrolysis and roasting for Sc_2O_3, TiO_2, $Ti(OH)_4$; electric arc furnace smelting, or reduction roasting and magnetic separation for iron; addition of phosphate for fertilizer production (Borra et al. 2016; Onghena et al. 2017; Chen et al. 2022). Commodity prices are indicated on Figure 4, which reflect volatility in the alumina price index (Ferraro *et al.* 2022) and for critical raw materials (Renner and Wellmer 2019), and also the cost of production, which is controlled by extensive use of reagents, the energy intensity of shipping and production along flowsheets. There is an 8-fold increase in commodity price from bauxite to alumina, and a 5-fold increase in commodity price from alumina to aluminium (Figure 4). The economic benefits of potential by-product generation would be realised at the site of alumina production.

Figure 5a, b, d demonstrates bauxite production for some of the leading global bauxite producers up to and including 2020: Australia (28.1% in 2020), Guinea (23.8%), China (16.8%), Brazil (8.9%), and India (5.3%). The increase in aluminium production rose steadily from 1970 to 1995 (Figure 5a), after which it increased dramatically in a profile (Figure 5b) that is similar to the increase in Chinese GDP as an effective proxy for global economic growth and the Great Acceleration (Purdy 2013; Steffen *et al.* 2015). The leading countries in bauxite production (Figure 5a, b, d) are not the leading countries in alumina production. Retention of the market share in the bauxite to alumina supply chain (indicator calculated as alumina production/bauxite production) is depicted in Figure 5f and it demonstrates that the retention of raw material within country is highly variable. Brazil (7.6%), and India (4.9%) have a similar proportion of the global production of alumina to bauxite. Guinea retains very little of the bauxite it produces and has just 0.3% of global alumina production, and Australia also has a lower proportion of global alumina production (15.5%) than bauxite production.

The lack of retention of mineral wealth (Figure 5) is most marked in the case of Guinea. There have long been plans to build alumina refineries in Guinea, with plans dating back to the time of Guinea's first regime under President Ahmed Sekou Toure (1958-1984). Within the Compagnie des Bauxites de Guinée (CBG) convention, there was a plan that the company would build a refinery within 10 years from when exportation started in 1973 (Diallo 2019). Subsequent regimes/governments have mentioned plans to emphasise refineries, used mining policy and various reforms, and/or put in place administrative processes to offer incentives to companies for the development of refineries. 50 years after the start of planning, policy reforms and studies, the plans to export alumina instead of bauxite have not been realised. In May 2022, Colonel Mamadi Doumbouya, the new junta leader, demanded that bauxite mining companies operating in Guinea would submit concrete and up-to-date plans to develop refineries (Jeune Afrique 2022). Colonel Doumbouya's demand placed significant pressure on mining companies with a presence in Guinea in May 2022. However, to date, the country is still waiting to see the materialisation of the new demands imposed by Colonel Doumbouya, given that the actions by stakeholders depend upon their economic and operational risk assessments.

Figure 6 summarises the material flows along the supply chain, using data for production, export and import, downloaded from the World Mineral Production mineral statistics database (BGS). China imports bauxite from both Australia and Guinea, as well as other nations, and produced 54.3% of global alumina. It plays a very important role in the aluminium supply chain, having either consumer or producer relations to every country in Figure 6, and being the largest exporter of alumina and aluminium to Russia, Japan, USA, UK, and Australia. China's largest import of bauxite is from Guinea, which is pivotal for China to increase the value of the product and retain profits, while simultaneously securing control of alumina and aluminium supply to multiple nations. Since Ga is primarily produced as a by-product of alumina (Torma and Jiang 1991; Butcher and Brown 2014), the 94% EU dependence on imports of Ga from China (European Commission 2023) is also unsurprising. The sites of aluminium production are more geographically dispersed than for alumina production, such that the retention of market share (indicator calculated as aluminium production/alumina production, Figure 5g) from alumina to aluminium production shows significant differences. Of the 5 case study nations investigated, India was most successful at retaining mineral wealth from the alumina to aluminium supply chain, while Guinea has no reported production of primary aluminium by smelting. When discussing location, it is also important to recognise the predominant North-South divide between primary consumer and primary producer countries (Figure 6), with consumers in the North and producers in the South. This may partly be a product of geographical locations of deposits, but it also reflects global wealth disparities and an appropriation of South commodities (worth $2.2 trillion in Northern prices in 2018; worth $152 trillion when accounting for lost growth between 1960 and 2018) by 'advanced economies' of the global North (Hickel *et al.* 2021).

Instead of building refineries, companies have focused on increasing exports of bauxite from Guinea. Société Minière de Boké (SMB), for example, announced the extraction of 34 Million tons raw bauxite from Guinea 2022, and the expected production of 36 and 38 Million tons respectively in 2023 and 2024 (Société Minière de Boké (SMB) 2023). Journalists associate this with in the takeover of "500 acres" of land since 2016 and a variety of other grievances (Chason and Sharrock 2023). There is an ongoing dispute between the Guinean government and Global Alumina Corporation (GAC) regarding the construction of a bauxite refinery, which was included in GAC's initial Mining contract (Afrique Vision 2023). The government insists on seeing those plans unfold while GAC has continued to export the raw bauxite that should have been processed at the promised refinery: the Guinean government now demands compensation for the losses resulting from GAC's exportation activities for a zone reserved for local transformation (Afrique Vision 2023).

Cultures of production

In this section, we transition from technical investigation to cultural investigation. The methodology here is to combine quantitative and qualitative data relating to the historical contexts of resource production with journalistic comment on current affairs, which are not yet fully quantified and analysed in a research context. The context we present is succinct and selective, to enable comparison of key traits of major bauxite-producing nations.

The Human Development Index (HDI, Table 1) reported by the United Nations is a measure of quality of life from most developed (1) to least developed (191). It is calculated by using life expectancy at birth, expected years of schooling and gross national income per capita. Australia has the highest HDI ranking of the bauxite producing nations (Figure 7), being defined by the United Nations as having 'very high human development'. Australia is the world's largest producer of bauxite ahead of Guinea (Figure 5), although it has smaller reserves (BGS 2009). It was a British penal colony between 1788 and 1901, after which bauxite was discovered (in 1952), and it now has active (Figure 8), though sometimes tense, trade relations with China (Zhou and Laurenceson 2022). With respect to the bauxite-aluminium supply chain, Australia is a *developed producer* economy.

China and Brazil have 'high human development' (Figure 7). China is a mass *consumer producer* of bauxite and plays an important role in controlling flows of profit and product (Figures 6 and 8). India and Indonesia are countries with 'medium human development' (Figure 7). India was first colonised by the East India Company in 1757 (Kumar 2017), and was officially a British colony between 1858 and 1947 (Figure 8), while Brazil was a Portuguese colony between 1500 and 1822 (Naritomi *et al.* 2012). Both India and Brazil are *emerging producer* economies with respect to the bauxite-aluminium supply chain, and India is included in Figure 8 as it commenced bauxite production in 1908 prior to independence from British Rule in 1947.

Bauxite mining commenced in a post-colonial context of nation building in some case study contexts, but it was concomitant with colonialism in Guinea (Figure 8). Guinea was a French colony between 1891 and 1958 and has since become an independent nation and a *developing producer* economy, heavily reliant on bauxite (and other) mining throughout its postcolonial state-building (Diallo 2019). However, Guinea has 'low human development' along with Sierra Leone, Mozambique and Pakistan (green triangle symbols; Figure 7). Compared to other bauxite-producing countries, Guinea has the lowest HDI (Table 1). To date, although bauxite mining contributed to the development of the Guinean post-colonial state and it continues to be a key contributor to the Guinean state budget, the high production of mineral resources in Guinea, particularly bauxite mining, has not led to economic growth for the populace at large.

Georgitzikis et al. (2021) succinctly summarise the regulatory and governance indicators in producing countries to establish risk for manufacturing/consumption in Europe, specifically using the Worldwide Governance Indicators (Table 1) and the Resource Governance Index. Georgitzikis et al. (2021) emphasise the extremely weak governance of Guinea and the weak governance of Sierra Leone, which supply 58% and 11% of European bauxite, respectively. Guinea has the smallest population and the smallest economy of the main bauxite-producing countries but the highest population growth rate, dependency ratio, unemployment, and life expectancy (Table 1). The trend of GDP per capita closely emulates that of the HDI rankings. The State dependence on mineral revenue in the face of high unemployment have overtime significantly contributed to frustrated expectations, grievances and protests both in mining regions and across Guinea. To date, successive colonial, dictatorial, military, and corrupt governing regimes have continued to focus on revenues from taxes rather than effectively exploring how mining can be a source of economic growth and structural transformation in Guinea (Diallo 2019, 2022). As Guinea has the largest reserves of bauxite and as it supplies significant consumer regions in China, Europe and elsewhere, it is important to examine the culture in which its position in the bauxite-aluminium supply chain evolved.

Bauxite was discovered in Guinea in 1891, so bauxite mining developed concomitant with colonisation (Figure 8). Guinea became an official part of 'L'Afrique Occidentale Française', or French West Africa following defeat in 1898 of Almany Samory Touré, Leader of the Wassoulou Empire. Despite the reform of Guinean civil rights between 1945 and 1953, dissatisfaction with the French presence and the lack of economic freedoms led to the election in 1957 of the anti-colonial Parti Démocratique de Guinée (PDG), headed by Ahmed Sékou Touré. Independence from France in 1958 was unique amongst French West Africa as it was not accompanied by socio-economic aid, with Guinea voting to cut ties with immediate effect: Touré famously spoke for the nation when he said "We prefer poverty in liberty than riches in slavery" (Diallo 2019). After cutting ties with France, Guinea was vulnerable, but was able to build strong alliances with Russia. In exchange for Russian exploitation of Guinea's bauxite resources, Russia provided Guinea with much-needed support ranging from military equipment and training, to capacity-building in different areas of the Guinean economy as a foundation for Guinea's postcolonial state-building efforts. The Guinea-Russia partnership proved to be mutually beneficial and helped Guinea establish itself as an independent nation and a critical player in the global mining industry (Diallo 2019).

Touré's nationalist and dictatorial regime was ended with his death, and it was followed by a military regime with a multiparty constitution, led by Colonel Lansana Conté from 1984 to 2008. The new economic landscape was aided by oppression and corruption that largely benefitted those with close connections to the presidency (Diallo 2019). Election rigging in 2002 and 2003 caused widespread strikes that impacted the economy and protests to demand improvements in standards of living, but mining still made up more than 80% of export revenues and 20% of GDP (Figure 8). A military coup, led by Captain Moussa Dadis Camara, created a new and equally authoritarian regime that terrorised and massacred peaceful protestors in 2009 (Amnesty International 2019). There are yet to be reparations for the 2009 massacre, but there is still a local and international outcry for recognition of the 150 lives lost, along with the hundreds of other victims (Amnesty International 2019).

Despite issues surrounding the 2010 election, it is regarded as the first democratic election in Guinea, and it was won by Alpha Condé, a high-profile opposition leader. Condé opened the economy to international investors, diverting resources in a corrupt pattern that extended political and economic control (Ostergard 2021). By 2016, bauxite exports had risen to 90% of national revenue and 25% of GDP. Under Condé's regime, there was an unprecedented increase of new bauxite mining companies in Guinea, which have increased the extraction of raw bauxite at the expense of ongoing environmental impact and social insecurity (Diallo, 2019, and unpublished data). Condé was credited with creating a mining powerhouse but failing to improve the lives of the population (Munshi and Hume 2021). There are claims that GAC's current and continued focus on exporting raw materials instead of alumina refining in-country is a legacy of advantages provided by the regime of Alpha Condé, which are now challenging for the current leaders to change (Afrique Vision 2023).

Condé was removed from power by a military coup on 5th September 2021, which caused significant commodity price volatility (Munshi 2021; Reid 2021). The coup leader Colonel Mamaday Doumbouya urged mining companies to continue operations, lifting curfews in mining areas (Munshi 2021) while the transition to civilian rule was managed. Prime Minister Mohamed Béavogui was appointed in October 2021 but, in his unexplained and indeterminate leave of absence, he was swiftly replaced by acting Prime Minister Bernard Gomou (Samb 2022), who was also dismissed in February 2024 when Doumbouya dissolved the Guinean government for a reshuffle leading to the nomination of a new prime minister – Mamadou Oury Bah (Samb 2022; Africa News 2024).

The military coup resulted in sanctions by the Economic Community of West African States ECOWAS (SMMNews 2021b; AfricaNews 2024). Meanwhile, Chinese stakeholders (SMMNews 2021b) stated that 'the soldier of the coup is a discerning man' and celebrated the remarkable achievements of Chinese bauxite mining companies in the 'kingdom of bauxite'. This stakeholder claim exists in a context of increasing Chinese Shares in Guinea mineral sectors that extend beyond bauxite mining, increasing export of raw bauxite from Guinea for resource security in China, and continued extreme poverty in the majority of rural communities in areas with new bauxite mining operations. Thus, mining revenues continue to profit only the mining company, and the state. With the highest reserves in the world (BGS 2009) and being a critical producer for the global aluminium industry, the export of bauxite from Guinea continued regardless of sanctions lifted in February 2024 (AfricaNews 2024). Because of the importance of Guinea in the aluminium value chain and the variety of its partners, the ECOWAS sanctions had no impact on Guinea's ability to continue its exchanges with partners in its bauxite mining industry. Moreover, the government always ensured that mining activities continued because it was the country's main source of revenue.

The dispute between GAC and the government of Guinea is an example of the challenges that mineral-dependent countries face and the complexities of resource governance in regime instability. Therefore, to ensure that companies commit to investing in local transformation and reduce the focus on extractives, there is a need for a regime with a vision and will to reinforce companies' commitment to invest in local transformation. On the other hand, as governments make demands, they must also ensure an enabling environment to implement these demands on the ground. In the case of Guinea, the need for more basic infrastructure can be a real challenge for the implementation of refineries. Therefore, negotiations between mining companies and the government also need to ensure that the longer-term vision includes a phased, realistic plan that can see the implementation of companies' commitments and government demands in line with a vision for inclusive development that will lead to economic growth. If the projects for refineries are implemented with no local capacity to work in these refineries, they will be run by foreign labour, have no impact on the socio-economic development of Guineans nor address Guinean issues such as youth unemployment, and contribute to mining conflicts. It is crucial for Guinea to build human resource capacity (World Bank Group 2015) as part of its phased approach to developing infrastructure and implementing refineries: while Guinea has one of the largest reserves of bauxite in the world, as well as significant iron ore, it has no state-of-the-art universities specialised in Science, Technology, Engineering, and Math, including Computer Science, and most universities do not have basic infrastructure such as 24/7 running water and electricity nor they have access to up-to-date software and equipment. Therefore, the country's aspiration to build refineries must be matched with the improvement of education systems and basic infrastructure (World Bank Group 2015; Camara *et al.* 2021).

Discussion of sustainability of the bauxite-aluminium supply chain

The sustainability issues of the bauxite-aluminium supply chain are related to the environmental, social, governance, and political impacts associated with the extraction, processing, and transformation of bauxite into finished products used in various sectors (including automotives, technology, aerospace, and other consumer goods). The issues vary between the countries where processes take place, and whether the activity is upstream or downstream in the global bauxite-aluminium supply chain. This research highlights only some of the issues related to sustainability.

At the up-stream end of the aluminium supply chain, the shallow nature of economic, laterally-extensive deposits means they are amenable to open-pit mining (e.g. Figure 3e). The process of mining starts with the clearing and removal of vegetation and topsoil, which is followed by overburden removal and then ripping or blasting, depending on the hardness of the deposit. The bauxite mining impacts water, soil and air quality, ecology and biodiversity, and local communities (Yadav et al., 2022; Diallo, 2020). It is a particularly acute challenge in tropical and sub-tropical climates where deforestation locally exacerbates the impacts of climate change (Sy *et al.* 2017; Parsons *et al.* 2021) and HumanRightsWatch (2018) expressed concerns over the impact of bauxite mining on populations dependent upon the wider environment in Guinea. Outside of West Africa, demands to cancel all agreements with bauxite mining companies, over concerns about environmental degradation in Orissa (India), were met with state terror in all its forms (Menon 2005; Kumbhar 2010; Ellis-Petersen and Hassan 2023). In Australia, with high regulations and governance (Table 1), a decision to sacrifice unique forested areas to maintain economic prosperity by bauxite mining is accompanied by requirements to restore natural forest into sustainable ecosystems that reflect the original forest prior to mining as much as possible (Tibbett 2012).

Production of bauxite in Guinea has increased nearly five-fold in ten years, from 17.6 million tonnes in 2011 to 87.4 million tonnes in 2021 (data from British Geological Survey, 2023). However, weak governance and lax environmental monitoring in Guinea (Diallo 2015, 2019), fails to prevent or mitigate negative impacts while bauxite mining activities escalate. The increasing extraction of bauxite in Guinea is becoming a typical case of neo-colonial development, through trade agreements with both former trade partners, and new global economic powers (Diallo 2015; Henri 2019; Udegbunam 2020; Hickel *et al.* 2021; Rapanyane 2021; Hairong and Sautman 2023). Regional efforts to open mineral strategic corridors from Africa to China, Russia, UEA and the EU are primarily about securing supplies of raw materials, though they might cite aspirations to boost societal development (Baranzelli *et al.* 2022). In the case of Guinea, the increasing extraction of bauxite to China, whilst contributing to the security of China's market, does not translate into local economic growth for the Guinean populace.

The expansion of bauxite mining activities in the past 10 year in Guinea, has put pressure on rural communities that depend on agriculture, and pastoral activities, and are struggling to maintain livelihoods. While economic partners applaud international contributions to infrastructure and economic development in bauxite-producer nations such as Guinea (SMMNews 2021b), the infrastructure that is developed by the new bauxite mining companies in Guinea within the last 10 years is largely concerned with the removal of bulk ore from mines to processing sites in trading nations where greater economic profit is generated. Therefore, arrival of new companies, and the increasing extraction of bauxite in Guinea has not led to structural improvement for the local community.

Environmental impacts are site-specific at sites of mining and processing, midstream in the supply chain (Figure 2, 6), and also dispersed due to the international transportation, and construction of transportation infrastructure (Onat and Kucukvar 2020). Waste is a significant issue at alumina processing plants and toxic waste spills have claimed human lives and devastated environments, in Hungary for example (Gelencsér *et al.* 2011; Winkler *et al.* 2018), emphasizing the need for effective monitoring, regulation and accountability throughout the supply chain. Further down-stream in the primary aluminium supply chain, the Hall-Héroult process of smelting involves electrolysis of alumina dissolved in an electrolyte. Aluminium smelting is a very energy intensive process that requires very reliable energy production scenarios, and it generates 61% of the greenhouse gas emissions of the aluminium sector worldwide (Georgitzikis *et al.* 2021). Figure 9 shows fossil fuel production (petroleum crude plus all types of coal) for nations that produce more than 1% of global aluminium, as a proxy for the relationship between metal production and fossil fuel burning. There are some exceptions to the general trend depicted. We note that Norway has domestic energy provision dominated by renewable sources (88.2 % hydroelectric power, 10.1 % wind power, 1.6% thermal power in 2022; Statista 2024) but it produced fossil fuels for export, so that it appears in the main trend. Iceland is omitted despite producing 1.1% of primary aluminium in 2020 because it likewise has energy security that is not reliant on fossil fuels (73% hydropower and 27% geothermal energy; Government of Iceland 2022). Click or tap here to enter text. Malaysia (36% natural gas) and Bahrain (83% natural gas) plot beneath the general correlation but they are also dependent on fossil fuels having a heavily reliance on natural gas, which was not included in the metric tonne-based calculations.

Fossil fuel energy dependence has created vulnerability for Europe- and US-based aluminium producers, who are reducing production because of the energy supply crisis related to the Russian invasion of Ukraine (Manthey 2022a). Meanwhile, aluminium smelters in Yunnan province, south-west China, account for 11% of China's aluminium output and are significantly reducing output by 800,000 tonnes due to a drought, being reliant on hydropower (Manthey 2022a). Increasingly severe climatic events, associated with climate change, affect all parts of the bauxite to aluminium supply chain, as evidenced by the closure of bauxite mines due to flooding in central Shanxi, China (SMMNews 2021a). Site-specific reductions in outputs have been accommodated with changes in the patterns of production and supply so that global aluminium production rose by 3.5% overall (Manthey 2022a). Thus, the geography of aluminium smelting is not simply a function of proximity to manufacturing regions because it also has a positive correlation with energy security and a powerful feedback loop with climate change and the use of renewable energy. The implication is that aluminium will continue to be available while it is needed for the low-carbon transition, but the sources and trading patterns of raw materials will be subject to continued and accelerating change.

Discussion addressing economic and development inequalities in bauxite production

Strategies in consumer regions such as Europe to improve resource security include vertical integration of supply chains by trade and direct offtake agreements, and by improving access to regional ore deposits (Baranzelli *et al.* 2022; BEIS 2022; European Commission 2022). The development of up-stream activities in the raw materials supply chain in Europe embodies a development of low-profit mining activities proximal to centres of manufacturing. Physical proximity of the whole, or a significant portion of the whole, supply chain reduces the distances required for transportation of bulk materials, such that the carbon footprint could be reduced. Smart approaches to reducing the carbon footprint of shipping (Lai *et al.* 2011; Hoang *et al.* 2022) should be more effective when processing of material occurs at the site of production to reduce waste and transport volumes. In short, the drivers for vertical integration in consumer nations are heavily influenced by security and environmental concerns, but the most lucrative deposits are located remote from centres of consumption and best accessed through trade agreements.

The Africa Development Bank (AFDB 2019) views vertical integration differently to the consumer nations, recognising that it may stem the flow of economic benefit away from producer nations. It aims to invest in infrastructure that facilitates national and regional development for down-stream economic activities (AFDB 2019). In this endeavour, it is supported by the earlier attempts of the military junta in Guinea to impose refinery construction deadlines on foreign companies, with Doumbouya stating at the time that '*despite the mining boom in the bauxite sector, we have to admit that the expected revenues are below expectations, and you and we cannot continue this game of fools that perpetuates great inequality in our relations*' (AfricaNews 2022). However, the debate about refineries is still on-going two years later. Promises to leverage Guinea's mining industry to drive social and economic growth is a recurring feature of every new leader in Guinea, but new governments have limited capacity to put pressure on mining companies since their government depends on this revenue. After the coup, the military junta was taking actions in an attempt to leverage a great position of power along the bauxite-aluminium supply chain, but as stated back in 2022 its success depends on an ability to unite the nation, build local human resource capacity through education and training, reduce corruption, and have a long term development plan coupled with the development of the mining sector (Diallo 2022). Today, Guineans have yet to see improved economic growth despite promises made by the military junta when they seized power.

The vertical integration of the up- to mid-stream segment of the aluminium supply chain within West African countries involves the development of processing facilities, so that mineral wealth can be retained within regional as far along the supply chain as possible. This would make a significant step-change towards realisation of the Sustainable Development Goal SDG 10, to reduce inequality within and among countries and to limit the impacts of the Resource Curse. However, it is dependent upon managing corruption, effective reporting and governance work to enforce best practice (Diallo 2022). For example, The Free Press newspaper of Ghana (Modern Ghana 2018) reported that the Ghana Revenue Authority had launched a full investigation into a case of corruption between the Chinese-owned Ghana Bauxite Company and Ghana Highways Authority who operate weigh-bridges, so that trucks could be overloaded and taxes of over US$90 million avoided over a six year period. It also remains to be seen how consumer nations respond to vertical integration within West Africa, since reduced inequality may negatively impact their respective economic performance, e.g. unrest in Guinea may disrupt flows of mineral wealth in post-colonial trading (Hickel *et al.* 2021; Nyabiage 2021). Currently, the majority of wealth creation is in alumina and by-product manufacturing centres (higher value commodities, Figure 4) removed from centres of production, so the development pattern of the supply chain essentially reinforces the removal of resource wealth from producer nations (Hickel *et al.* 2021).

The global distribution of bauxite ore deposits means that it is entirely feasible for a region to restructure its trade patterns: Malaysia, Russia, and India became the three largest suppliers to China in 2020 (GlobalTrade 2021). Nevertheless China has locked Guinea into a $20 billion dollar loan, in exchange for bauxite concessions (Samb 2017), such that it has significant financial leverage and rights for almost 2 decades, and thus a neo-colonial control of the country. These types of loan, and ties, increase dependence on foreign investment instead of vertical development, and exploration of growth by economic diversification. The development of infrastructure whereby the trade-colonial investor nation recovers their economic investment over the long term as well as achieving the removal of mineral capital, is described by Enns and Bersaglio (2020): as mega-infrastructure projects with 'colonial moorings' that serve the interests of global capital rather than local and indigenous peoples being promised more modern, prosperous futures. The strategies to secure resources for manufacturing and consumption focus on transparency and responsibility of supply chains, and decoupling resource production from conflict generation (Georgitzikis *et al.*

2021). They centre around the interests of citizens in consumer regions in a pattern of extractivism that is exemplified in the case of Guinea, but to a much lesser extent in Australia, because the colonial trade spillovers are negatively correlated with geographical distance to the former colonising power (Berthou and Ehrhart 2017). Thus, political instability and poor national wealth is exploited and financial aid is contingent on resource wealth extraction (Diallo 2019).

In Guinea, the only aging Friguia refinery is operating far beneath full production, plans for development of refineries are early stage, and analysts do not anticipate there will be new greenfield alumina refinery development before 2026 (Christopher 2023). The Russian-owned Rusal bauxite mining company therefore has significant leverage in Guinea, as evidenced by reports that it could withdraw Russian personnel from its three major mines and the Friguia alumina refinery after the 2021 military coup (Devitt and Heinrich 2021), given that it has the capacity to divert ore between refineries internationally (MiningTechnology 2022). However, Rusal had also negotiated better pay and living conditions with striking miners (Samb *et al.* 2022), since effective community relations are essential for economic wealth generation and to manage unrest that results from the Resource Curse whereby local communities fail to benefit from mineral wealth (Cocks 2017). Amadou Bah, the executive director of Action Mines, a charity that monitors Guinea's mining industry attests that Rusal creates '*enormous economic benefits for a Russian oligarchy that has considerable weight in the political and economic affairs'* of Guinea (Maclean 2019). Thus, successful actions to reduce inequalities based on corporate social responsibility (Harvey 2014) are presently those that support established patterns of economic wealth concentration. Actions to reduce inequalities by more evenly dispersing wealth in ways counter to the established economic paradigm (i.e. sequestering mineral wealth by processing in producing nations) will likely be resisted by powerful governments, and companies owned and operated from developed nations.

Greater retention of mineral wealth in producer nations that currently export unrefined bauxite ore, by locating minerals processing proximal to mining centres, constitutes a reorganisation of the bauxite-aluminium supply chain with implications for both socio-environmental and trade relations. (1) Such a reorganisation needs implementation of appropriate environmental protections to manage process-related wastes, appropriate human capacity development to ensure job opportunities, collaboration with local communities to co-create responsible mining approaches which will mitigate the impact of mining on local communities, and their environments, and effective monitoring and implementation of environmental regulations by the government (Diallo 2022). (2) Vertical integration in producer countries is a reorganisation that is likely to be perceived by the investor nations as a significant economic loss (Hickel *et al.* 2021). Investing stakeholders are more likely to agree to compensation than the loss of economic revenue, or to agree at climate conferences to a reduction in the use of fossil fuels (Maslin *et al.* 2022). Alternatively, they may accuse competitor nations of protectionism, if there is an attempt to down-stream or to green the economy using tax credits for fair trade schemes (Parker *et al.* 2022). Actions are thwarted by individual nations seeking to avoid becoming the 'losers' in the globalization of the low carbon transition, as well as negotiating issues of trust (Maslin *et al.* 2022).

The Terrestrial Actor is the response of the natural world to the loads imposed upon it (Latour 2018), irrespective of progress towards global policy agreements, and it limits the future of globalization (Ehrenfeld 2005). This is observed in the bauxite-aluminium supply chain by extreme weather events (e.g. flooding or droughts), energy constraints, and social and military unrest arising as a consequence of between- and within-nation economic inequalities. While capacity exists globally to reshape the patterns of the bauxite-aluminium supply chain in response to shocks, there is a tension between reorganisation for greater sustainability and protection of multi-national interests. Recent events in Guinea demonstrate that actors within resource-producing nations are prepared to take significant actions to combat the Resource Curse. In 2023, Indonesia decided to ban bauxite exports in order to grow the economy by domestic down-streaming, replicating its success in developing domestic processing of nickel since 2020 (Manthey 2022b). Furthermore in 2022, Zimbabwe banned the export of lithium in an effort to ensure that the country develops an upper-middle income economy (ZM 2022).

In order to defray risks, China is encouraging private enterprises to develop small-scale projects in Africa (Nyabiage 2022). In Guinea, although regulation promotes employment of Guineans in the mining sector, and development of mining related projects, regarding the development of small-scall mineral projects, the technologies and infrastructures that are deployed require imported expertise and therefore, the majority of Guineans cannot benefit from the development of mining activities. Unless development offers the opportunities to contribute to structural change through widespread opportunities beyond a largely incomer elite group, it is impossible to expect growth and meaningful development from the mining sector. Moreover, the boundaries of what constitutes small-scale mining are subject to interpretation, but the regulations for small-scale mining need to be fit-for-purpose on a sliding scale towards medium- and large-scale operations on laterally large ore deposits of bulk metals. The potential for mining communities to be marginalised at a local level and the role of small-scale mining needs careful consideration (Moore *et al.* 2020; Sidorenko *et al.* 2020; Johnson *et al.* 2024).

Conclusions

Bauxite, or bauxite/aluminium, is a critical raw material for the European Union that is processed initially into alumina, which is then smelted to aluminium metal. Gallium is a critical metal by-product of the alumina refining process and shocks relating to bauxite production may create secondary shocks for gallium. A suite of additional high-value, by-product critical raw materials might in the future be extracted at the alumina refining stage: scandium, gallium, lithium, cobalt, titanium and REE. Aluminium, gallium, and the additional potential critical raw materials are of strategical significance to the energy transition for building the infrastructures and technologies of renewable energy, and light-weighting transportation for lower energy consumption. However, the shipping of unrefined bauxite ore and the energy requirements of aluminium refining are very high, such that the bauxite-aluminium supply chain exemplifies the mineral-energy nexus.

Vertical integration involving more mining proximal to regions of greatest consumption is limited by the geology and the geographical distribution of optimal weathering environments. Thus, vertical integration is premised on ensuring strategic mineral corridors are developed that ensure stable and secure supplies by trade negotiations. A responsible supply chain will conside r the compound criticality of the bauxite-aluminium supply, which additionally concerns sustainability and stewardship initiatives, and it should engage upstream countries in discussions about the economic opportunities arising from designations of materials as critical.

Where alumina refining is distal from bauxite mining regions, then the producer nations are effectively excluded from the most lucrative current and potential future economic opportunities arising from the low carbon transition and by-production of critical raw materials. Vertical integration in producer nations requires retention of mineral wealth and development of the supply chain within nation. The extent of vertical integration depends on capacity building in a stable regime, which is impacted by the Resource Curse, post-colonial and neo-colonial structures. However, international companies and stakeholder countries can support and advocate for inclusive, transparent and win-win business engagements in upstream industries. Accessing the Guinean resource where repeated calls for refinery development by foreign companies are not realised, for example, requires companies to position themselves as a partner of choice for the country and the people. It also requires countries to build the human and capital resources needed to ensure that the wider population can take advantage of opportunities that are offered by the mining sectors, and to monitor and mitigate negative environmental damage, ensuring that mining areas are effectively rehabilitated and monitored.

Environmental sustainability is intractably intertwined with socio-economic stability and pathways to greater transparency, responsibility and benefit to local populations. Aluminium output at individual sites is impacted by climate-change related events but there are enough production centres globally (of bauxite, alumina and aluminium) that decreased production due to high-risk local events (flooding, drought, conflict) are accommodated by changing patterns of material flows. However, societal-environmental tensions in the bauxite-aluminium supply chain might be exacerbated and become more frequent, due to the combined effects of climate-change related events and trade neo-colonialism, widening challenges that impact access to strategic bulk metals.

Acknowledgements

C. Beeson is given photo credits (Figure 3a-c). P. Diallo acknowledges the mining companies and communities of Guinea for access and co-operations. E. Deady is acknowledged for supportive internal review. R. Herrington and an anonymous reviewer are acknowledged for formal reviews.

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Table 1. Worldwide governance indicators and social indicators (Georgitzikis *et al.* 2021) and demographic characteristics (World Bank Group 2023a) in case study countries. HDI = Human Development Index (United Nations 2023a). Dependency ratio = (people younger than 15 or older than 64)/(the working-age population aged between 15 and 64), as the proportion of dependents per 100 working-age population. GDP = Gross Domestic Product. Australia has the highest performance in all social indicator categories.

	Australia	**China**	**Guinea**	**India**
Worldwide governance indicators - percentile ranks (higher number is better performance)				
Voice & accountability	93.1	6.4	26.1	57.6
Political stability; absence of violence & terrorism	88.6	38.1	17.6	21.4
Government effectiveness	92.8	71.6	21.2	59.6
Regulatory quality	98.6	42.8	21.2	48.6
Rule of law	93.3	45.2	9.1	52.4
Control of corruption	94.2	43.3	18.3	47.6
Social indicators				
Resource governance index (mining, 2017)	71		38	
Conflict risk - HH INFORM (2021)	0.0	6.3	4.1	7.0
Fragile state index (2020)	24.1	69.9	97.2	75.3
Global Peace Index (2020)	1.3	2.2	2.1	2.6
Child labour (%, last available data)			24.9	4.3
Global slavery index (2019)	1.0	2.7	4.0	2.7
HDI (most [1] to least [191] developed)	5	79	182	132
Demographic characteristics (World Bank, 2019)				

Life Expectancy (yrs)	83	77	62	70
Population (million)	25	1,410	13	1,300
Population Growth per year (%)	0.2	0.1	2.7	0.2
GDP per Capita (USD)	59,934	12,556	1,174	2,277
Unemployment Rates (%)	5.1	4.8	6.3	6
Dependency Ratio (%)	56	42	84	48
Literacy Rates (%)	*n/a*	97	40	74
Access to Electricity (%)	100	100*	44.7	99
Access to Internet (%)	90	70	26	43
Women in Government (%)	31	25	17	14

* As reported by The World Bank (2020). The accuracy of the data is not always well known. For example, there is evidence provided by (Zhang *et al.* 2022) that many rural households in China are dominantly reliant on the usage of straw and firewood, suggesting an inequality of access to electricity similar to that found in countries categorized with lower overall human development.

Figure captions

Figure 1. The cross-cutting issues of criticality and potential co-production of critical raw materials (CRM) and recycling of aluminium. (a) Economic importance and supply risk are used to define commodities as critical raw materials (European Commission 2020b), here critical risk of supply shortage is depicted for potential by-products from the bauxite to aluminium supply chain using the 2020 CRM risk list. (b) Access to secondary sources of aluminium (assuming 100% of end-of-life scrap by 2050) is projected to contribute up to 61% of supply, so primary extraction of bauxite deposits will continue to increase in magnitude regardless of recycling efficiency (graph from Hund et al. 2022). (c) Concentrations (ppm) of CRMs in bauxite from selected localities in the Tethyan belt (data from Herrington et al. 2016). TREE are total rare earth elements, a chemical group used in the manufacture of high-tech consumer products and to advance low-carbon technologies (particularly permanent magnets). B&H is Bosnia and Herzegovina.

Figure 2. Map of the world showing key sites of production in the bauxite to aluminium supply chain. The bauxite-producing nations used as case studies to examine supply chains are Australia, Brazil, China, Guinea and India. The locations of bauxite production around the Mediterranean Sea correlate with the ore deposits in the Tethyan Belt (Figure 1c). Centres of aluminium processing are located closer to centres of critical metal consumption, than to centres of bauxite production. Map reproduced with the permission of © CRU International Ltd. 2023. All rights reserved.

Figure 3. Photographs of bauxite variability (a-c) and mining in Guinea (d-f). Bauxite samples are: (a) pisolitic bauxite from Les Baux, St. Remy de Provence, France – the type locality for karstic bauxite; (b) Belterra Clay Horizon, Lower Amazon Basin, Brazil; (c) lateritic bauxite from Sierra Leone. Images of samples in the museum of the Camborne School of Mines courtesy of C. Beeson. Field images from the Kindia region of Guinea: (d) bauxite outcrop and the natural forest that is removed for mining, (e) a modern LSM operation and (f) mine access road demonstrating multiple land use and co-existence with farming communities.

Figure 4. Schematic overview of the recovery process of intermediate products and by-products between bauxite and aluminium, showing that the high value products are produced at sites of alumina production and aluminium smelting rather than at the location of bauxite production. The simplified Bayer and additional processes (excluding hydrolysis, chlorination and pyrometallurgy) are based on the various extraction schemes and flowsheets of: Borra et al. (2016); Onghena et al. (2017); Narayanan et al. (2019); Chen et al. 2022). Click or tap here to enter text.The concentrations of major and minor components in bauxite and red mud are from: Deady et al. (2016); Herrington et al. (2016). The commodity prices are quoted as US$/metric tonne (USD/mt) or as US$.kilogram (USD/kg) and sourced from the *Institute of rare earth elements and strategic metals*

https://en.institut-seltene-erden.de/aktuelle-preise-von-basismetallen/ (commodity price correct, 5 December 2022). Products such as aluminium fluoride and aluminium alloys have commodity prices of 1370-1441 USD/mt and 1460-2085 USD/mt, respectively.

Figure 5. Production in Australia, Brazil, China, Guinea and India of (a, b) bauxite, (c) alumina and (d) aluminium. The long-term production data shows a relatively consistent rate of increase prior to 1995, at which point production and consumption accelerate markedly. The market share between the top5 5 producers is normalized to 100% in (e), for the purposes of depicting retention of mineral wealth within country. The retention of mineral wealth within country is indicated for the top 5 producers as a scaled bar for alumina relative to bauxite (f) and primary aluminium relative to alumina (g), derived from ratios of commodity production data. All figures derived using data from the World Mineral Production mineral statistics database (British Geological Survey 2023).

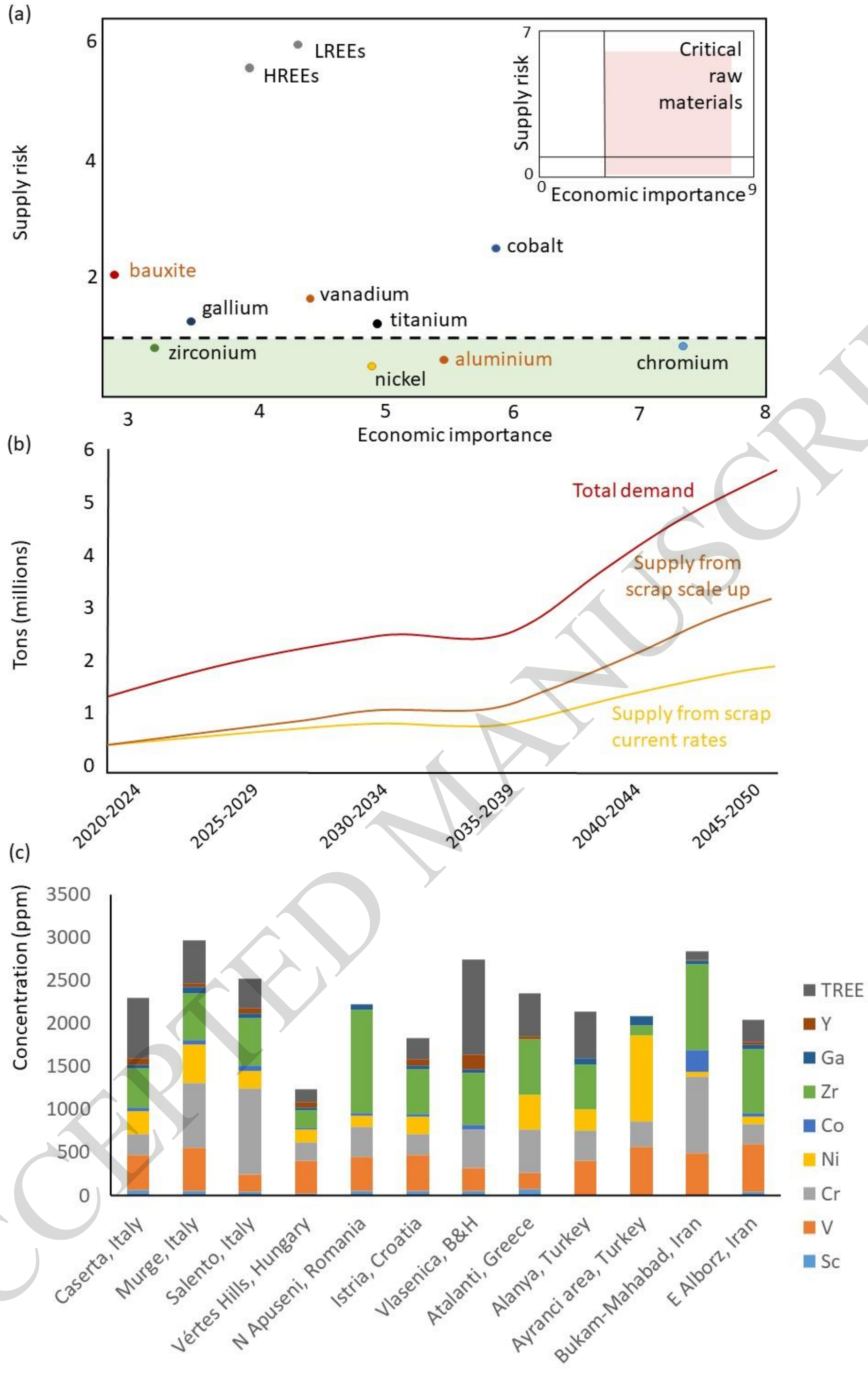
Figure 6. Centres of major production (P) and major consumption (C) of bauxite and its derivative products, specifically alumina and aluminium, demonstrating the dominant material flows and trading networks. The heavy arrow shows the largest import for a country. The data for production, export and import derives from the World Mineral Production mineral statistics database (British Geological Survey 2023).

Figure 7. Graph depicting the relationship between bauxite production (as a percentage of global production; data from the Mineral Statistics Database, (British Geological Survey 2023) and development of a producing nation (as Human Development Index (United Nations 2023a). * Sierra Leone, Mozambique and Pakistan

Figure 8. Selected significant events in the political and bauxite extraction histories of countries that produce more than 5% of global bauxite: Guinea, India, Australia and China. SMB, Société Miniére de Boké is the largest bauxite mining company in Guinea. Data compiled from: Dorian 1989; Roche and Mudd 2014; Toma and Tohănean 2018; Diallo 2019; Cavoli et al. 2020; Soni 2020.

Figure 9. Graph depicting the general correlation between production of primary aluminium and fossil fuel (petroleum crude plus all types of coal) production as a proxy for current energy security, within nations that have more than 1% of global primary aluminium production. Iceland produced 1.1% of global primary aluminium in 2020 but is not depicted, having no reliance on fossil fuels for energy security. All types of coal were included in the calculation because of variability in national reporting in the World Mineral Statistics Database (British Geological Survey 2023). Malaysia and Bahrain are beneath the correlation trend being more reliant on a fossil fuel base that is heavily dependent on natural gas, which was not included in the calculations. Norway has domestic energy provision dominated by hydroelectric and wind power, but produced fossil fuels for export.

Figure 1



(a)
Supply risk
Economic importance
LREEs
HREEs
cobalt
bauxite
vanadium
gallium
titanium
zirconium
aluminium
nickel
chromium
Critical raw materials
(b)
Tons (millions)
Total demand
Supply from scrap scale up
Supply from scrap current rates
2020-2024
2025-2029
2030-2034
2035-2039
2040-2044
2045-2050
(c)
Concentration (ppm)
TREE
Y
Ga
Zr
Co
Ni
Cr
V
Sc
Caserta, Italy
Murge, Italy
Salento, Italy
Vértes Hills, Hungary
N Apuseni, Romania
Istria, Croatia
Vlasenica, B&H
Atalanti, Greece
Alanya, Turkey
Ayranci area, Turkey
Bukam-Mahabad, Iran
E Alborz, Iran

Figure 2

Figure 3

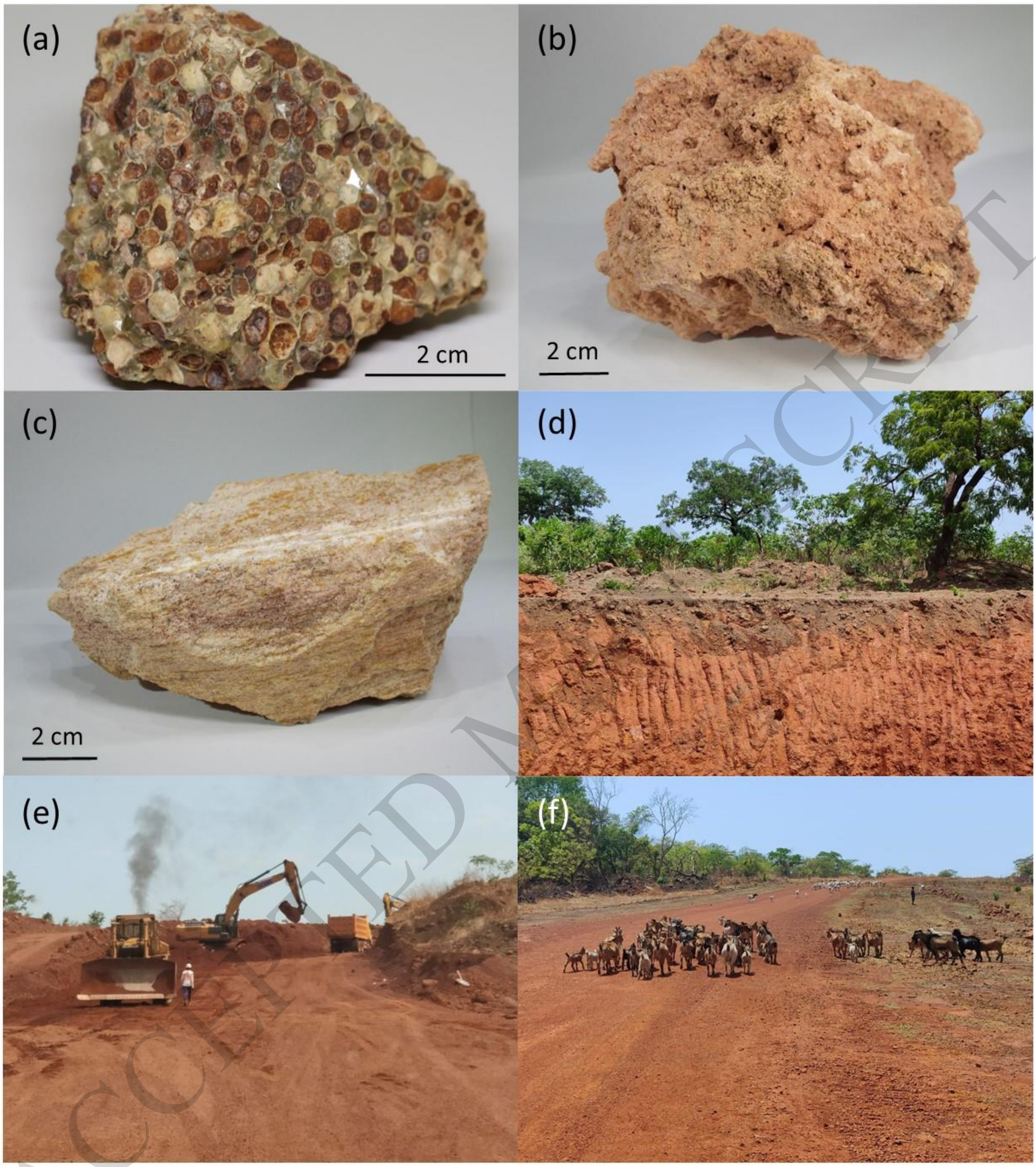


Figure 4

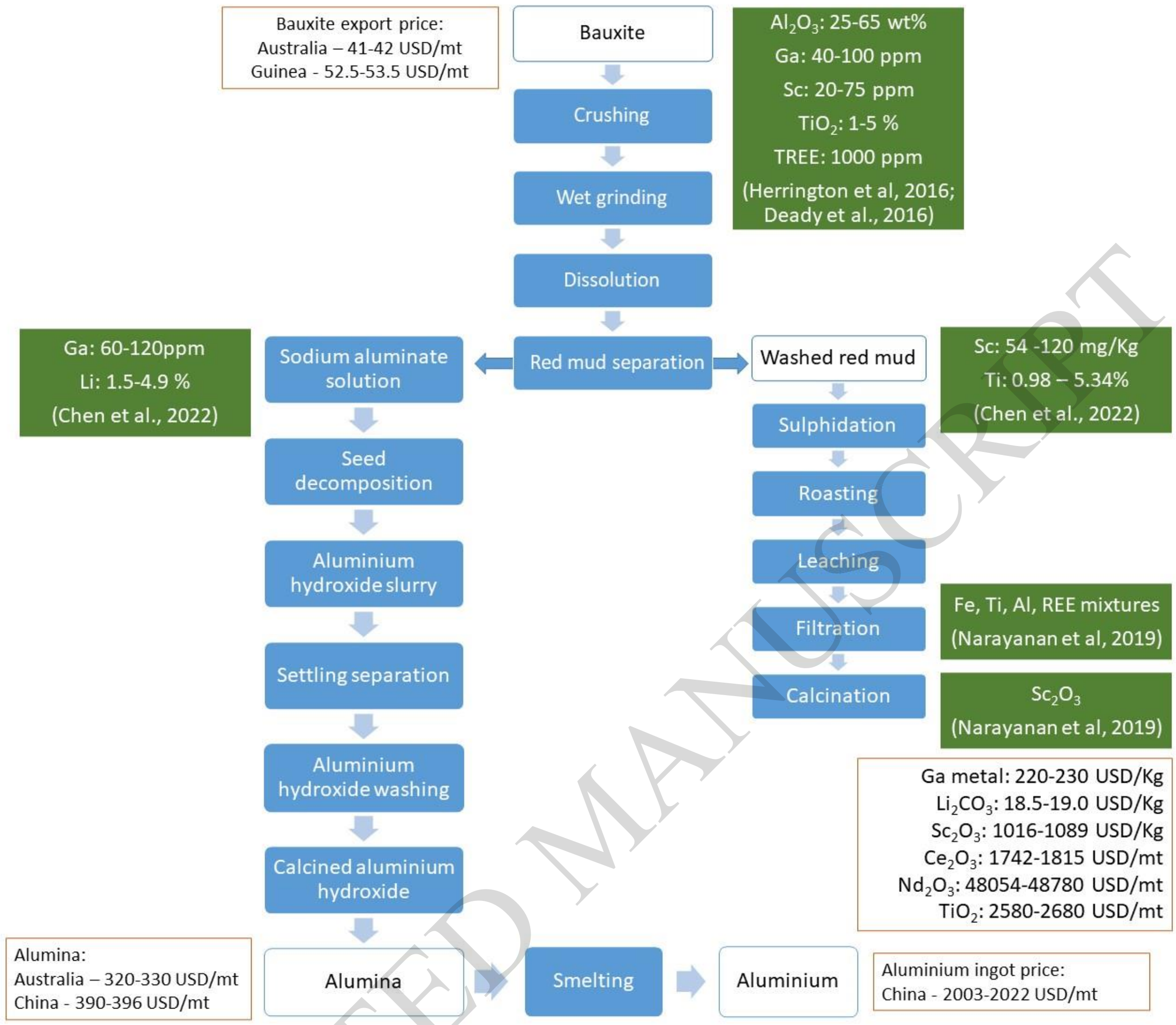
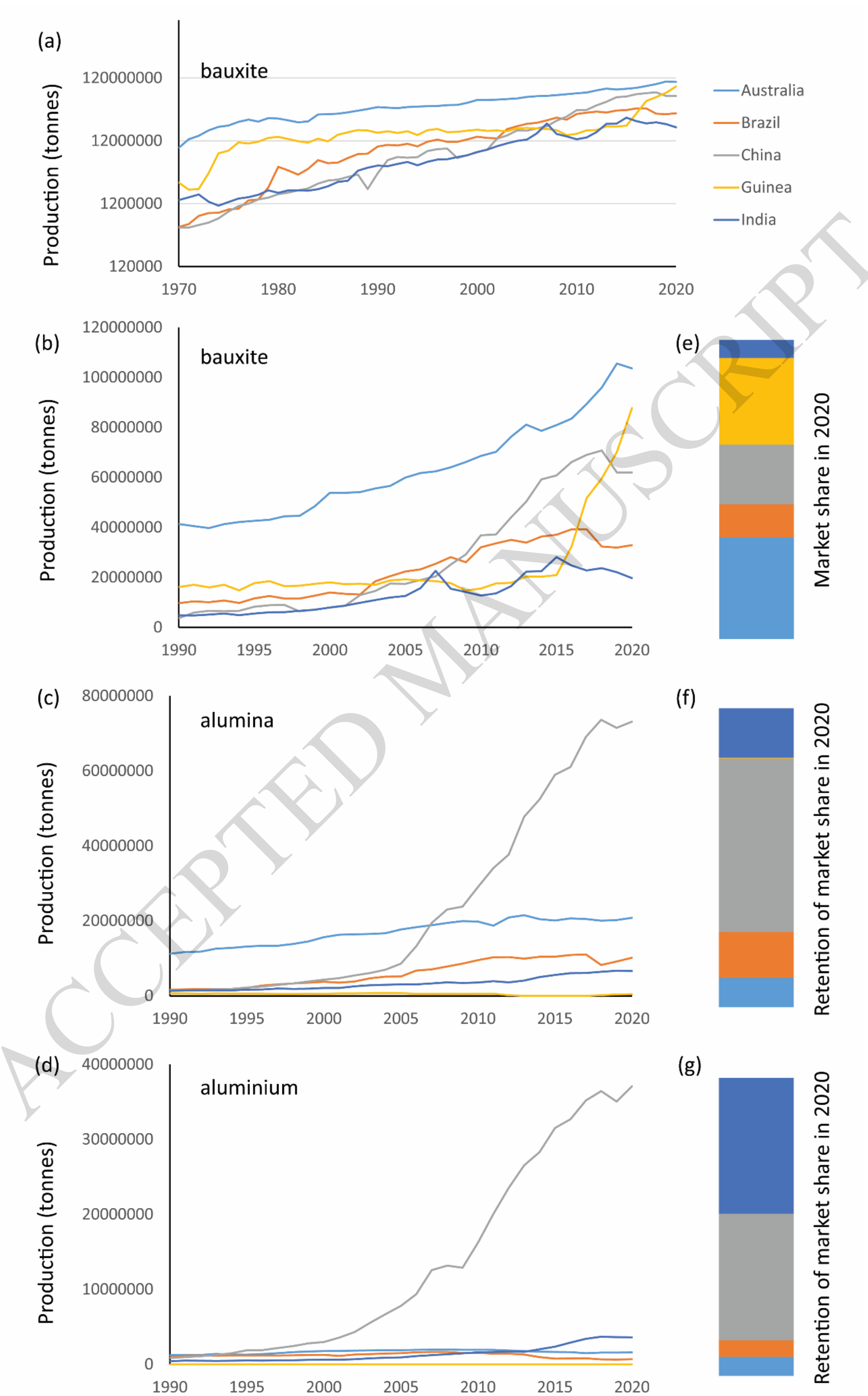

Bauxite export price:
Australia – 41-42 USD/mt
Guinea - 52.5-53.5 USD/mt
Bauxite
Crushing
Wet grinding
Dissolution
Al_2O_3: 25-65 wt%
Ga: 40-100 ppm
Sc: 20-75 ppm
TiO_2: 1-5 %
TREE: 1000 ppm
(Herrington et al, 2016; Deady et al., 2016)
Ga: 60-120ppm
Li: 1.5-4.9 %
(Chen et al., 2022)
Sodium aluminate solution
Red mud separation
Washed red mud
Sc: 54 -120 mg/Kg
Ti: 0.98 – 5.34%
(Chen et al., 2022)
Seed decomposition
Sulphidation
Roasting
Aluminium hydroxide slurry
Leaching
Filtration
Fe, Ti, Al, REE mixtures
(Narayanan et al, 2019)
Settling separation
Calcination
Sc_2O_3
(Narayanan et al, 2019)
Aluminium hydroxide washing
Ga metal: 220-230 USD/Kg
Li_2CO_3: 18.5-19.0 USD/Kg
Sc_2O_3: 1016-1089 USD/Kg
Ce_2O_3: 1742-1815 USD/mt
Nd_2O_3: 48054-48780 USD/mt
TiO_2: 2580-2680 USD/mt
Calcined aluminium hydroxide
Alumina:
Australia – 320-330 USD/mt
China - 390-396 USD/mt
Alumina
Smelting
Aluminium
Aluminium ingot price:
China - 2003-2022 USD/mt

Figure 5



(a)
bauxite
Production (tonnes)
120000000
12000000
1200000
120000
1970
1980
1990
2000
2010
2020
Australia
Brazil
China
Guinea
India
(b)
bauxite
Production (tonnes)
120000000
100000000
80000000
60000000
40000000
20000000
0
1990
1995
2000
2005
2010
2015
2020
(e)
Market share in 2020
(c)
alumina
Production (tonnes)
80000000
60000000
40000000
20000000
0
1990
1995
2000
2005
2010
2015
2020
(f)
Retention of market share in 2020
(d)
aluminium
Production (tonnes)
40000000
30000000
20000000
10000000
0
1990
1995
2000
2005
2010
2015
2020
(g)
Retention of market share in 2020

Figure 6

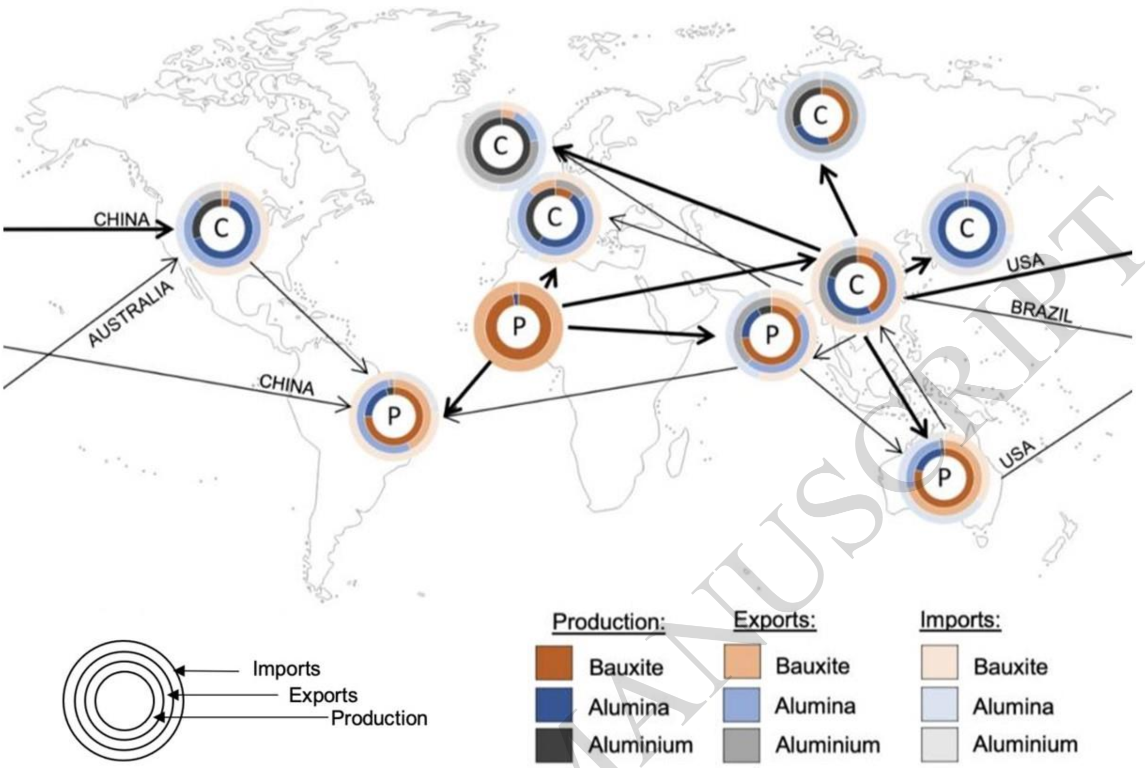

CHINA
AUSTRALIA
CHINA
USA
BRAZIL
USA
C
P
Imports
Exports
Production
Production:
Bauxite
Alumina
Aluminium
Exports:
Bauxite
Alumina
Aluminium
Imports:
Bauxite
Alumina
Aluminium

Figure 7

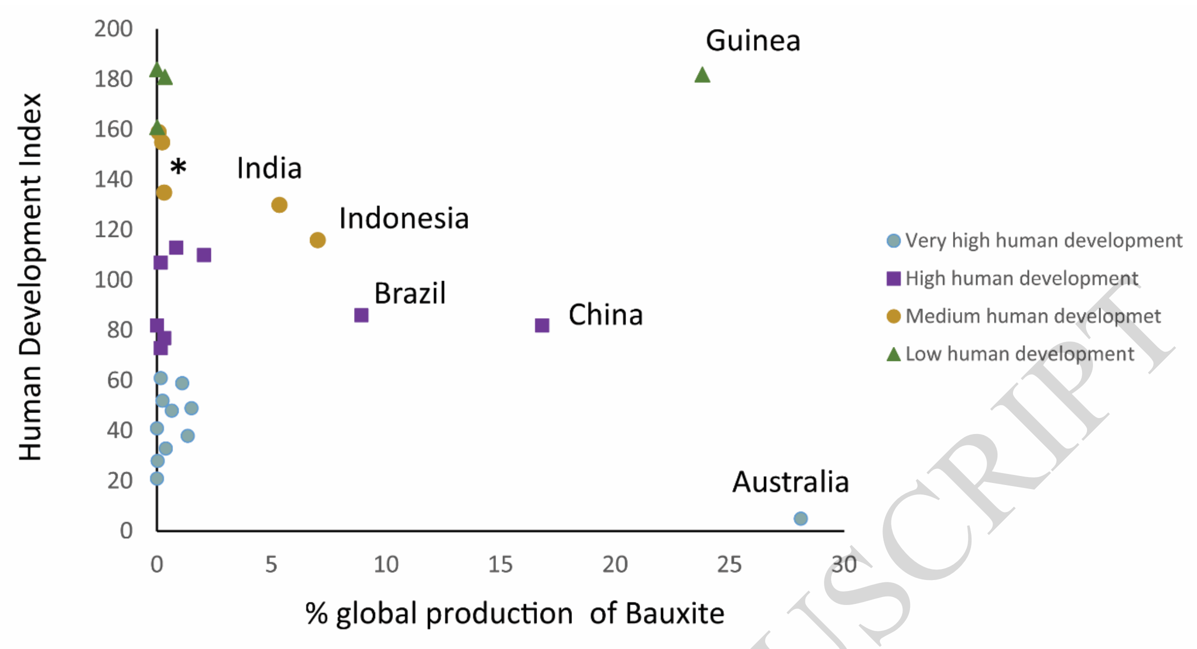
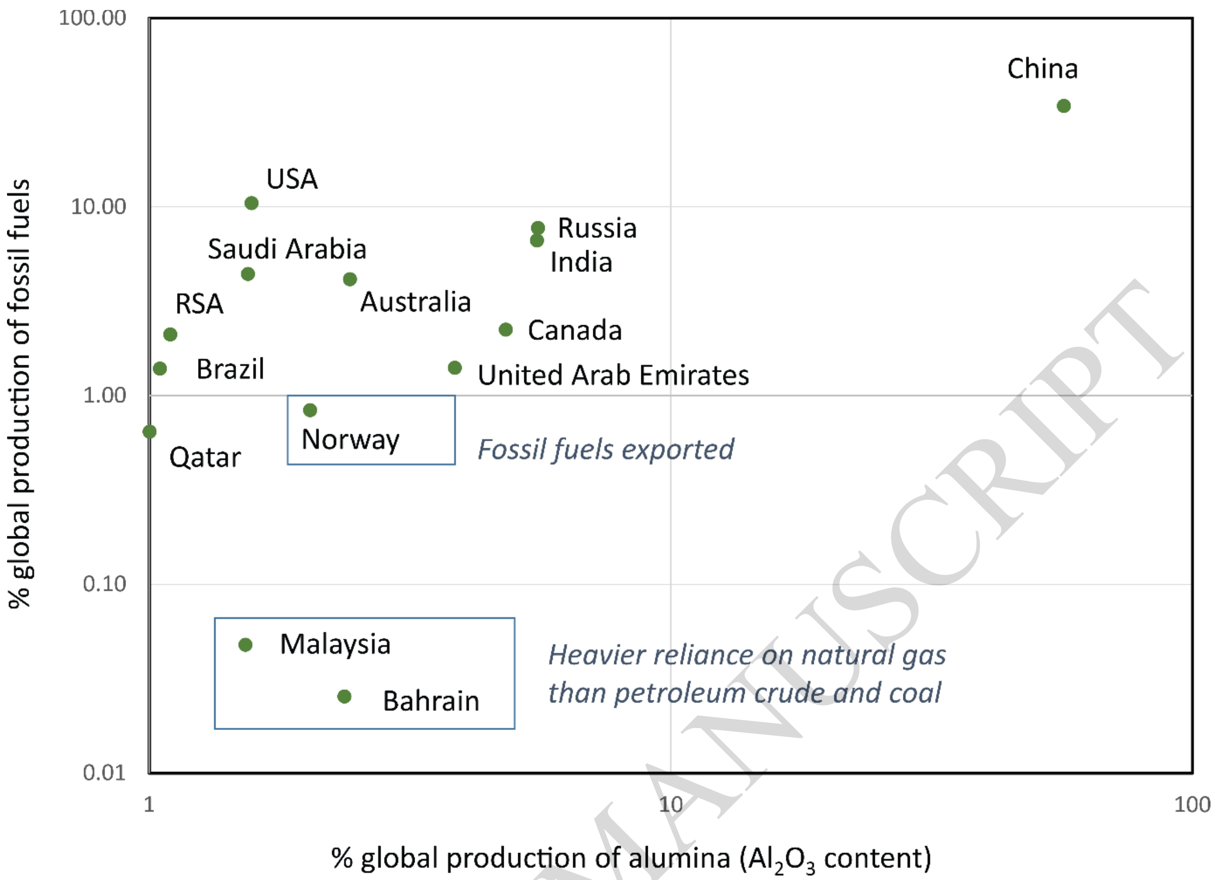

Guinea
India
Indonesia
Brazil
China
Australia
*
Human Development Index
% global production of Bauxite
200
180
160
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
Very high human development
High human development
Medium human developmet
Low human development

Figure 8


Guinea: developing producer
2021: Military coup removes Condé & causes volatility in bauxite commodity price
2017: Riots in Boké bauxite mining hub
2016: Mining makes up 90% of revenue and 25% of GDP
2010: Alpha Condé elected new president of Guinea
2008: Lasana Conté dies; military coup follows. Mining is 40% of total exports, worth US$596 million
2005: Mining is 80% of exports and 20% of GDP
1984: Lasana Conté becomes president after a military coup and the death of Touré
1958: Ahmed Sékou Touré becomes president following independence
1989: Guinea becomes part of French West Africa
1891: Bauxite is discovered in Guinea and a French colony is established
1500: Guinea becomes part of an essential trade route for European countries
India: emerging producer
2021: India emerges as third largest aluminium supplier to China, behind Malaysia and Russia
2010: Environment agency prevent Verdanta mining from extracting bauxite in the Nyamgiri Hills
2000s: Ongoing oppositions and human right violations in Orissa
1998: State Government blacklists NGOs supporting activists objecting to bauxite mining in Orissa
1975: vast bauxite deposits discovered along east coast in Orissa and Andhra Pradesh
1947: India gains independence
1908: bauxite first mined in India
1885: Indian National Congress able to govern by consensus
1858: British Government established rule over India
1844: Construction of railways and canals
1757: British East India Company expands control after the Battle of Plassey
Australia: developed producer
2021: Aluminium trade agreement - tensions over China-Australia strategic Economic Dialogue
2015: Calls for tighter environmental protections from cumulative impacts of bauxite mining
2000
1993: Aboriginal people win land rights
1972: 'White Australia' immigration policy ends
1960-1962: Aboriginal Australians granted citizenship & can vote
1952: Bauxite first discovered by Northern Territory Coastal Patrol Service
1917: Trans-Australian railway opened
1901: British Government creates the Commonwealth of Australia
1900
1788: First penal colony established
1770: Captain James Cook explores and claims Australia for the British Empire
China: consumer-producer
2022: Chinese aluminium smelters are impacted by power shortages and work to decarbonize
2021: China closing the most polluting smelters & increasing imports
2018: Ghana Revenue launches investigations into Chinese bauxite mining company for evading taxes
2013: Launch of the 'One Belt One Road' initiative announced to resurrect dynastic trade routes.
2010: Economic Cooperation Framework Agreement
1999: Launch of the 'Go Global' strategy
1997: Hong Kong returns to China from British rule but retains a capitalist economy
1980s: Most LSM operations for bauxite established
1966: The Cultural Revolution leads to the imposition of martial law and 1.5 million deaths
1949: People's Republic of China follows civil war
1912-1949: Republic Period after collapse of dynastic system

Figure 9



100.00
10.00
1.00
0.10
0.01
1
10
100
% global production of fossil fuels
% global production of alumina (Al_2O_3 content)
China
USA
Russia
India
Saudi Arabia
Australia
RSA
Canada
Brazil
United Arab Emirates
Norway
Fossil fuels exported
Qatar
Malaysia
Bahrain
Heavier reliance on natural gas
than petroleum crude and coal