Bundesanstalt für
Geowissenschaften
und Rohstoffe

Aluminum

Sustainability Information

July 2020

AT A GLANCE

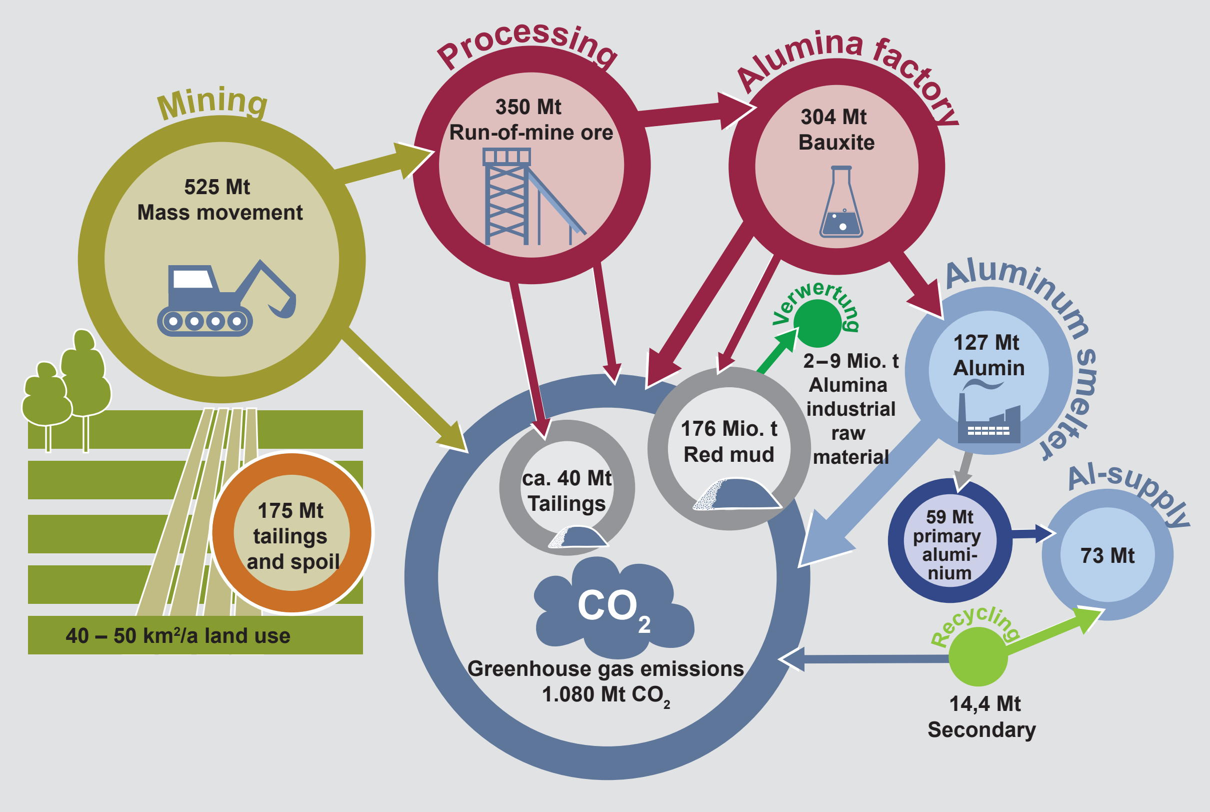

Fig. 1: : Calculated mass flows in aluminium production and principal effects on the environment, data from 2017 [1].

- Most of aluminium‘s added value comes from processing the bauxite ore and not from mining. The principal bauxite producers are Australia, China and Guinea; the largest primary aluminium producers are China, Russia, Canada and India.
- Bauxite deposits are thin and shallow. Mining therefore has a large specific land requirement. However, for the same reasons, the excavated land is relatively simple to recultivate.
- Aluminium production is extremely expensive in terms of energy. The true primary energy consumption in the production chain, and therefore the CO_2 emissions depend on the status of the adopted technology and, to a greater extent, on the available primary energy mix.
- Due to the relatively low energy costs (only 5 % compared to primary aluminium) aluminium recycling plays an important role, but the majority of the aluminium used in vehicles and infrastructure is not yet available for recycling.
- Land use conflicts in ongoing or planned projects have been reported from Guinea, Brazil, India, Ghana and Vietnam.
- In the Aluminium Stewardship Initiative (ASI), more than 100 companies in the added value chain have committed to adhere to sustainability standards and their review.

CONTENT

1 RELEVANCE

Aluminium is a silvery-white light metal which, due to its material properties – high electrical and thermal conductivity, low density, high resistance to environmental influences, high strength-to-weight ratio – is used in Germany in particular in construction (15 %), automotive and aircraft engineering (48 %), in the mechanical engineering and electrical engineering fields (14 %), and as packaging material (10 %) [1]. With a consumption of 2.1 Mt worldwide, Germany is the third largest consumer of primary aluminium after China (33.3 Mt) and the USA (4.6 Mt) [2].

In the transport sector, the light metal aluminium reduces vehicle weights. The level of development of today‘s aircraft industry and in aviation would otherwise be impossible to achieve. 100 kilograms less car weight, so says the car designers‘ rule of thumb, reduces fuel consumption for 100 km of driving by up to half a litre of fuel, which corresponds to an emission saving of approx. 11 g CO_2 per km. In automotive engineering the transition from a steel body to an aluminium body saves around 150 kg in weight [3]. According to one automobile manufacturer, the increased energy consumption required to produce aluminium would be compensated for by the fuel savings after about 60 – 80 thousand km, but only if renewable or CO_2-neutral energy sources were used as primary energy sources in aluminium production.

The parent rock, bauxite, is not only exploited for aluminium production, but also for other purposes, in particular for Portland cement, proppants and the refractory industry, as well as for abrasives and mineral wool. In 2015 approx. 12 Mt of bauxite were used globally for these purposes.

2 FROM DEPOSIT TO METAL

Aluminium is extracted from bauxite ore, which is first leached in order to produce the raw material aluminium oxide, also known as alumina, using the Bayer process. The alumina is then converted into pure aluminium in a primary aluminium smelter using melt flux electrolysis, in what is known as the Hall-Héroult process.

2.1 Geology

Although aluminium is the third most frequent element involved in the structure of the earth‘s crust, it is not sufficiently enriched in primary rocks to be economically extracted from them. It is only when the primary rock is weathered that the aluminium is enriched in concentrations that are worth mining.

Bauxite is a residual rock formed from the weathering of a variety of rocks, generally igneous. These source rocks were exposed to weathering over long periods (millions of years) under tropical, subtropical or very humid, temperate conditions. Today, 90 % of known global bauxite deposits are located in tropical or subtropical countries.

The largest deposits of bauxite are located in Central and South America, in West Africa, especially in Guinea, as well as in India, China, Vietnam and Australia. Some occurrences are also known from northern Russia, the Mediterranean region and Saudi Arabia. The currently estimated global bauxite resource is more than 70 billion tonnes. The greatest concentration of deposits is in located Guinea, where there are proven resources of around 25 billion tonnes [4]. The aluminium content in the deposits is differently distributed regionally. The deposits in Indonesia and Australia have an average aluminium oxide content of approx. 40 %, in America and the Caribbean the levels are approx. 48 % and the highest levels, at 53 %, are found in West Africa. Australia has extremely rich bauxite deposits in the north, which mainly produce bauxite for export. The deposits in the south of Australia, in contrast, are regarded more as the „poor“ deposits and are predominantly processed domestically. The global average content of metallurgical – i.e. used for aluminium production – bauxite is approximately 45 % aluminium oxide.

The aluminium content of the bauxite ore is a decisive factor for the effort (e.g. energy expenditure) necessary for further processing the bauxite in an alumina plant in order to produce alumina from it. For this reason, mainly high-quality bauxite ores from Guinea, Liberia and Northern Australia are imported into Germany. In principle, the karst-bauxite districts are distinguished from the laterite-bauxite districts (Fig. 2). Compared to the lateritic deposits, the karst bauxite deposits are usually smaller, but due to their higher aluminium oxide content they have a more favourable – because reduced – bauxite-to-alumina ratio. In the long term, the proportion of bauxite production from karst deposits, which in 1996 was approx. 20 % of total production has been reduced to a few percent today.

2.2 Mining

Many bauxite deposits are shallow and horizontal, with only 0.5 to 1 m cover. Typical bauxite deposit

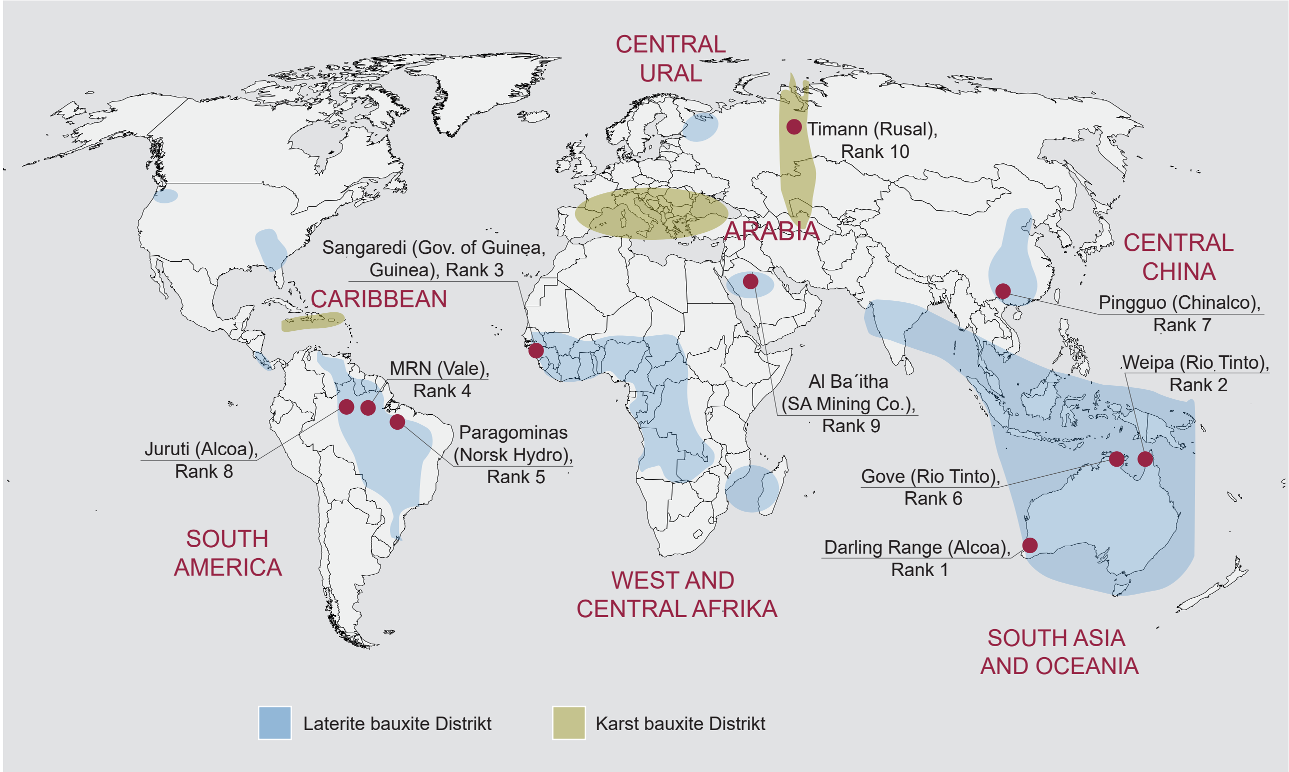

Fig. 2: *The 10 largest bauxite producers and locations of the bauxite provinces and districts, (modified after [17] and [19]).*

thicknesses are between 2 m and 10 m. Due to the stratigraphic relationships, bauxite is almost exclusively extracted in open-cast mining.

The bauxite from many deposits can be processed directly as raw ore in alumina plants, also called refineries, without further treatment. In some cases, however, the bauxite ore must be upgraded in a washing plant where the aluminium oxide content of the raw ore is increased by removing accompanying clays and silicate nodules. Typical bauxites consist of approximately 45 % aluminium oxides. In addition, bauxite also contains iron, silicon and other minerals. The mineralogical composition of the bauxite is important because it influences process engineering and the metallurgical results in the production of alumina.

In 2018, 342.5 Mt of bauxite were mined worldwide and were processed into 130.5 Mt of aluminium oxide (Al_2O_3). From this, 62.6 Mt of primary aluminium were extracted. The global ratio of bauxite to alumina to primary aluminium calculated from this is 5.2 t of bauxite : 2.2 t alumina : 1 t primary aluminium. Deviations from these averages can be explained by variations in the aluminium oxide content of the bauxite and the alumina, as well as by the differences in the output of the metallurgical processes.

In 2018 Australia (96.5 Mt) was the world‘s largest bauxite producer, followed by China (79 Mt) and Guinea (59.5 Mt) [2]. The largest alumina producers are China (69 Mt), Australia (20 Mt) and Brazil (11 Mt). Together, these 3 countries produced three quarters of the alumina produced worldwide in 2017. In the same year, China (32 Mt) was also the largest primary aluminium producer with almost half of global production, followed by Russia (4 Mt), Canada (3 Mt) and India (2 Mt) [4]. Although the demand for aluminium is increasing rapidly, the known bauxite reserves are sufficient to meet global demand for aluminium for many centuries.

Aluminium is mainly produced by vertically integrated, internationally positioned, specialised raw material groups. „Vertically integrated“ means that both bauxite mining and its processing (alumina and aluminium production) are under the control of a single company. In the case of Rio Tinto, South32 and Vale, they may also be more broadly based conglomerates that mine a variety of raw materials. The market leader alongside Rio Tinto is the Alcoa group, which specialises in producing and marketing aluminium only. It can be seen that a relatively large number of the major aluminium producers worldwide are in state hands or that states hold high shares in these companies. These „state-owned“ companies include RUSAL (Russia), Chinalco (China), NALCO (India), but also Norsk Hydro (Norway, 33 % state share). The reason for the high level of state participation in the aluminium industry is, on one hand, a traditional link between the state and the strategic aluminium sector, and on the other, the necessity for high investments planned over the long-term, which encompass energy infrastructure, above all. Norsk Hydro also owns the German primary aluminium producer Vereinigte Aluminium-Werke AG.

Bauxite (content >52 % Al_2O_3) as a high-quality raw material for the refractory industry or for use as an abrasive medium can be obtained in industrialised small-scale mining with a production capacity of approx. 10 kt – 200 kt per year – this is the case, for example, in Guyana, Brazil and India. The prices for sintered bauxite, for example, can be more than 10 times the price of metallurgical bauxite and thus also allow small-scale mining to be profitable. Due to the low price of metallurgical bauxite of approx. $US 30 – 45/t small-scale mining for this raw material is usually not economical, especially since bauxite extraction is associated with high transport costs. The share of small-scale mining in bauxite extraction is therefore negligible on a global scale.

2.3 Processing

In metal production, a distinction is made between primary aluminium, which is obtained from bauxite, and secondary aluminium from aluminium scrap. The production of primary aluminium from the bauxite raw material can be divided into four main process steps: 1. Grinding and leaching, 2. Aluminium hydroxide calcination to form aluminium oxide. 3. Smelting the alumina and 4. Electrolysis of the aluminium oxide melt and separation of the liquid aluminium phase.

The first two process steps take place in what is referred to as a refinery or alumina plant (Fig. 3). Here the alumina (aluminium oxide) is produced from the raw bauxite ore. The ground bauxite ore is leached by adding hot caustic soda solution and lime in pressure vessels at temperatures between 120 °C and 300 °C and pressures of 40 – 200 bar. Generally, the higher the temperature and pressure, the better is the metallurgical aluminium oxide yield, in particular with regard to poorly leachable bauxite minerals. The aluminium is present in the solution as sodium aluminate and is then separated from the leaching residue (primarily iron oxide, calcite and silicates) by filtration. The leaching residue is washed out and, after dehydration, deposited in a red mud landfill. Depending on the aluminium content of the bauxite, around 0.5 – 1.5 tonnes of solid waste remain per tonne of alumina produced. The pure aluminium hydroxide is precipitated and calcined to aluminium oxide (Al_2O_3 >99%) in a rotary kiln or in a fluidised bed reactor at temperatures of 1,200 – 1,300 °C. This alumina forms the starting material for fused metal electrolysis.

The Hall–Héroult process is used for industrial aluminium metal production from alumina (Fig. 4). In the first smelting process stage, alumina is melted in a molten bath of cryolite (Na [AlF]) - a fluorine-containing salt that reduces the melting temperature of the alumina, which would otherwise be over 2,000 °C, to 950 – 970 °C.

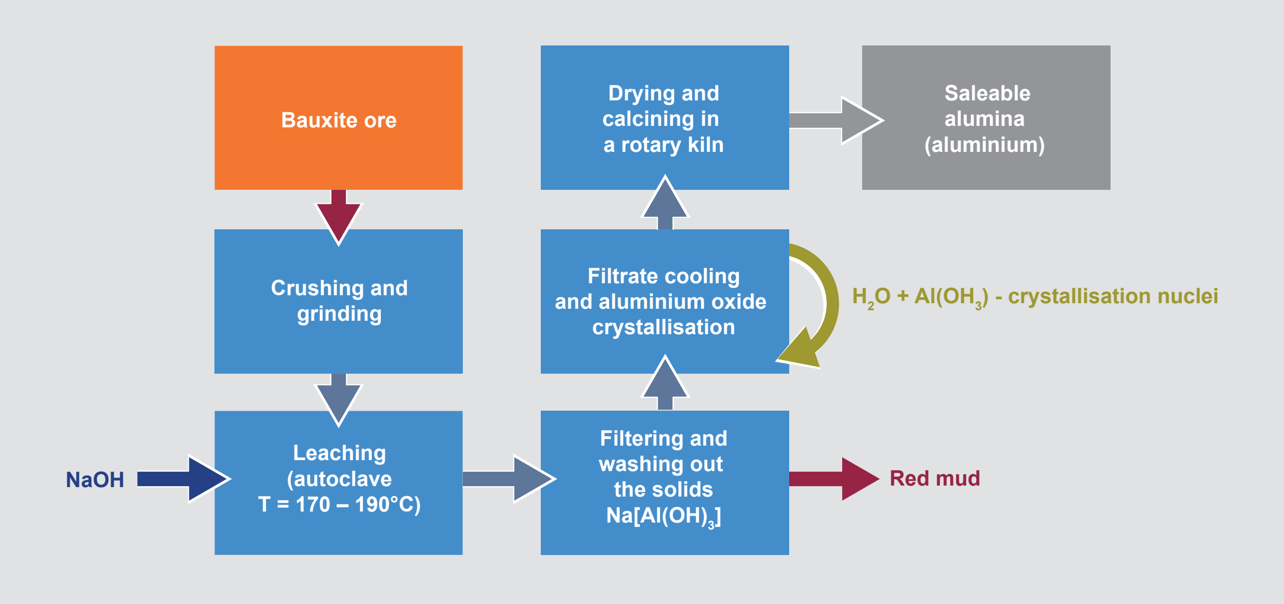

Fig. 3: *Bayer process schematic (modified after [6]).*

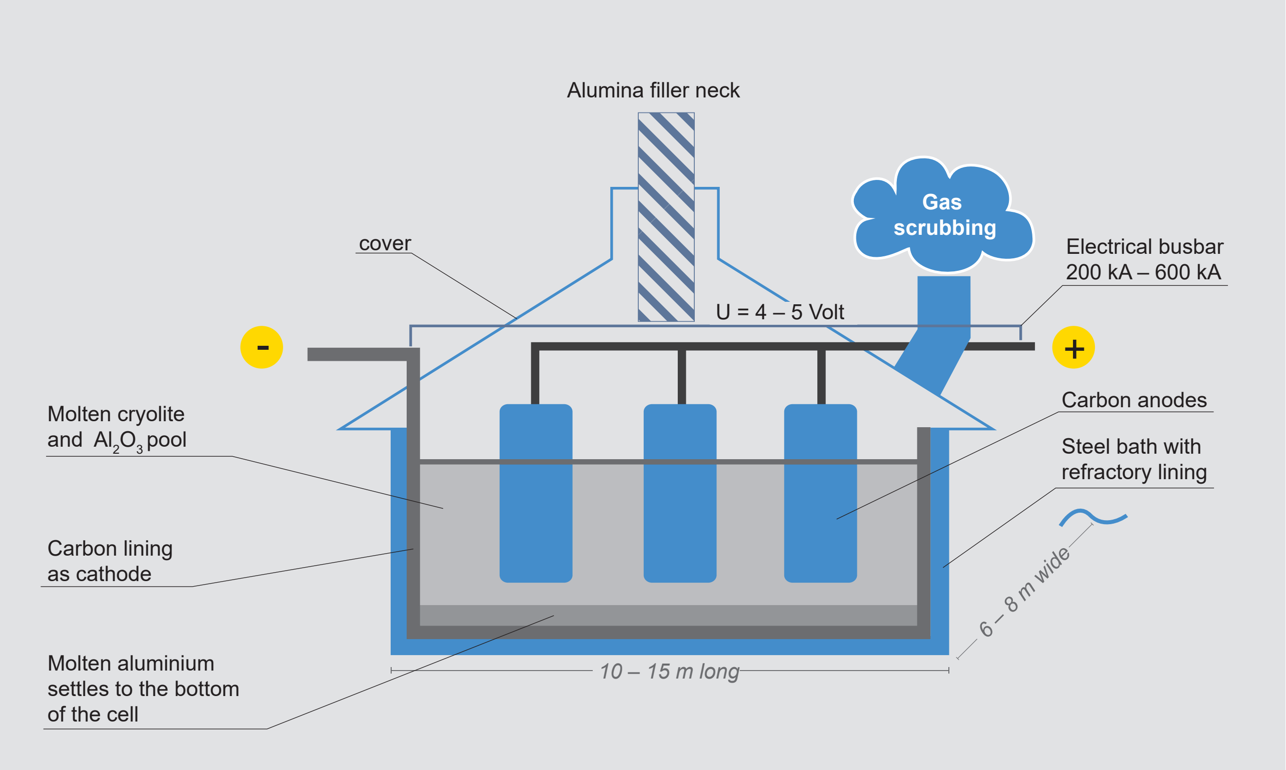

Fig. 4: *Hall-Héroult cell schematic.*

Electrochemical reduction of the molten aluminium oxide to aluminium takes place in the electrolysis furnaces (steel tanks lined with ceramic materials and carbon) by applying a direct voltage between the carbon anode and the carbon cathode in the tank bottom. These furnaces are connected in an electrical series in what is known as a „potline“, which contains up to 300 individual furnaces or cells. The current flow – up to 300,000 amperes – in the cell serves on the one hand to keep the tank temperature constant at 950 – 970 °C, and on the other it causes the electrolytic precipitation of the liquid aluminium on the tank bottom. From there the liquid aluminium is drawn off and delivered to the foundry in special vehicles, where it is cast into cast alloys, rolling ingots and extrusion billets. The anodes consist of petroleum coke and tar pitch and are consumed during electrolysis in an anode reaction, whereby the oxygen released from the aluminium oxide by the molten bath reaction reacts with the carbon of the anode to form carbon monoxide (CO) and carbon dioxide (CO_2).

With regard to the furnace technology, a distinction is made between the older Söderberg technology – here the one anode mass is continuously baked due to the heat radiation in the cell during process electrolysis – and the newer prebaked technology, in which the anodes are baked separately before use in the furnace. Prebaked technology offers advantages in terms of environmental protection and process energy savings. Aluminium production is an energy-intensive process that causes around 1 % of global greenhouse gas emissions [5]. In the context of energy consumption and the servicing effort for the equipment in alumina production, as well as energy consumption and fluoride emissions in the smelting process, the technologies used today can be classified and evaluated in 3 categories with regard to efficiency and sustainability [6]. However, all of these technologies are still justified within their business context.

- **Outdated:** Leaching in an autoclave, calcining in a rotary kiln, electrolysis in cells with Söderberg anodes

  Energy consumption per t Al in the Bayer process: 412 kWh electricity + 712 mN³ natural gas; energy consumption per t Al using electrolysis: 15,548 kWh electricity;

  This technology leads to high gaseous emissions (CO_2, fluoride, perfluorinated hydrocarbons).

- **Modern** (but not widespread): Leaching in a tube reactor, calcining in a fluidised bed, electrolysis in cells with prebaked anodes and the most recent cell technology

Energy consumption per t Al in the Bayer process: 412 kWh electricity + 496 mN³ natural gas; energy demand per t Al using electrolysis: 13,473 kWh electricity + 62 mN³ natural gas;

This is currently the most advanced technology with the lowest emissions.

- **Standard:** Leaching in an autoclave, calcining in a fluidised bed, electrolysis in cells with prebaked anodes and older cell technology.

  Energy consumption per t Al in the Bayer process: 412 kWh electricity + 672 xmN³ natural gas; energy consumption per t Al using electrolysis: 14,273 kWh electricity + 62 mN³ natural gas

  This is currently the standard technology.

The most advanced technology therefore saves approx. 20 % primary energy. With further design and operational improvements, it will be possible to reduce the electricity consumption during electrolysis from currently approx. 13,200 kWh/t to 11,200 kWh/t, especially in newly constructed electrolysis halls [7].

3 RECYCLING

Globally, aluminium recycling covers around 30 – 40 % of total use [8]. An average of approx. 15,700 kWh of electrical energy are required to produce one tonne of primary aluminium. Recycling only requires around 5 percent of the energy used in primary production. Three quarters of all aluminium ever produced (since the 1880s) is still in productive use [9]. In 2019 this stock had grown to more than 700 million tonnes [10]. About a third each of the productively utilised aluminium is used respectively in buildings (windows, roofs, cladding, etc.), transport (automobiles, aircraft, etc.), and machines and cables.

Secondary aluminium (recycled aluminium) is currently playing a role in the major economies, in particular: of the total of 14.4 Mt global supply of secondary aluminium, 43 % is used in China and 25 % in the USA, followed by Japan (5.6 %), Germany (5.3 %) and Italy (5.1%). In Germany it covers more than 1/3 of consumption, which is currently approx. 2.1 Mt [4]. The technical effort required to recycle aluminium is low due to the low melting temperature of 500 °C, meaning that aluminium is also recycled on a small-scale in numerous developing countries and is not recorded in global statistics.

4 SUSTAINABILITY ASPECTS OF MINING

In the case of aluminium, as the most important non-ferrous metal in terms of production volume, the large quantity of material required annually compared to many other metals alone entails a corresponding production footprint. Only for iron, gold and copper, with more than 2 Bt each, is an even larger volume of raw material extracted. Approx. 5–7 tonnes of bauxite (moist raw ore) and 3 tonnes of barren rock or spoil must be removed and transported to produce 1 t of aluminium. This means that an average of 7–9 t of solid residues are produced in the various processes of production and extraction for one tonne of primary aluminium.

4.1 Environmental aspects

Land requirement and mining residues

Because the bauxite deposits are usually stratified, horizontal and relatively thin, large mining progress is necessary over the area in order to ensure a high production capacity. An open-cast mine with an average production of 2 Mt of bauxite per year and an assumed average deposit thickness of 5 m would result in a mining area of approx. 20 hectares (about 40 football pitches) for mining the ore alone – without taking into account the areas for the required open cast embankments. In addition, further areas for temporarily stockpiling spoil and product heaps, as well as transport routes and processing, would be necessary.

On average, mining takes up a little less than one square metre of land (including roads and infrastructure) to produce one tonne of aluminium metal. The annual global encroachment on uncultivated land directly or indirectly related to bauxite mining, is estimated at around 40 to 50 km².

The second largest bauxite mine in the world, Weipa, which is operated by Rio Tinto in Australia, has an annual capacity of 31 Mt of bauxite (approximately 10 % of world production) and resources of 1.2 Bt of bauxite with an area of approximately 2,600 km². Since it was commissioned in 1964 until 2012, 68 km² of this concession area has been mined. An approximately 4 km² area of the mined land is currently recultivated every year, which roughly corresponds to the annual mining rate. By 2012, more than 50 km² of land had been recultivated and replanted.

Bauxite is often mined in tropical or subtropical zones, some of which are arid, as in Australia, or have a very humid climate, as in West Africa. As a result, the soils that are available for recultivation are usually extremely poor in nutrients and make targeted recultivation of the excavated areas difficult. In tropical countries, however, natural succession, favoured by high precipitation, leads to relatively rapid regrowth on the mined area. As a rule, this natural regrowth is supported and supplemented by operational measures. „Best practice“ is the use of the soil strata removed and separately stockpiled prior to the actual bauxite extraction as a substrate to prepare the land for recultivation, whereby the original stratification should remain as unchanged as possible during reinstallation. An important measure in the recultivation of excavated areas is flattening the peripheral slopes in order to guarantee erosional stability.

Because the deposits are shallow, the volume of spoil that needs to be moved on average before the bauxite is extracted is relatively small compared to other metallic raw materials, and is between approximately 0.33 – 1.5 t spoil per t bauxite. Due to the extensive mining, it is often possible to move the spoil around in the open cast mine and to use it as backfill for recultivation. In the Australian mines approximately 0.24 m² area per tonne of bauxite are currently recultivated, which corresponds to an annual area of approx. 20 km² [20].

Biodiversity

Often, recultivation cannot reinstate the original condition of the ecosystem, as shown by the Weipa example. Post-mining rehabilitation in Weipa was only able to partially compensate for the loss of habitat caused by clearing. 23 years after recultivation measures began, mining still has an obvious influence on biodiversity, meaning that one third of the native forest birds are still absent, for example [11].

In the principal mining countries of Guinea, Jamaica, India, Australia and Brazil, primary forest is also partially destroyed for mining, which results in a loss of biodiversity. It is assumed that approx. 20 % of the area used annually for bauxite mining is located in tropical rainforests [18].

Emissions

Mineral waste: Bauxite washing, which is not always necessary, is intended to increase the aluminium content of the bauxite and remove reactive silicon oxide, which would increase the consumption of reagents in refining or disrupt the leaching process, at an early stage. As a rule, only hydromechanical methods and processes are used for this purpose in washing. The waste is a fine-grained sludge that must be stored in sludge ponds. These sludges, which are extremely low in nutrients and are made up of clays, quartz and bauxite minerals, can account for up to 15 % of mining production. Depending on the location of the wash relative to the mine, the sludge is either deposited in the vicinity of the washing plant in sludge basins or it can be used to backfill the open pits. In both cases, special measures to protect groundwater are not generally required.

Groundwater

Because the groundwater table is usually below the level of the shallow bauxite deposits, groundwater lowering is generally not necessary to operate the open cast mine.

4.2 Social and socio-economic relevance

Social and socio-economic aspects

In some cases the livelihoods of indigenous peoples are threatened by mining – such as in the case of bauxite mining in the Niyamgiri Mountains in India, for example [12]. In any case, including the indigenous population groups as important interest groups in any decision about extracting raw materials is internationally recognised standard procedure. This is widely practised in Australia, for example. The Gulkula bauxite mine in northern Australia, which is run by Australian Aborigines and where only Aborigines work, produces around 500,000 tonnes of bauxite annually for the aluminium producer Rio Tinto.

Local residents, environmentalists and non-governmental organisations have made allegations against the operators of some bauxite projects. Controversial projects include the Sangaredi project in Guinea, the Juruti (Alcoa) and Oriximina (Mineração Rio do Norte, MRN) projects in Brazil, the UAIL project in Kashipur and the Nyamgiri-Vedanta aluminium complex in Orissa, both located in India, the planned bauxite mine in the Alew Forest in Ghana and the Tan Rai bauxite project in Vietnam. In these projects, the dispute often revolves around land use and compensation issues, as well as possible environmental impacts. The issue of resettlement as a reason for conflict is particularly important in India. Land use conflicts are also known from the Boké bauxite district in Guinea. Here, the Compagnie de Bauxites Guinée (CBG) is accused of not having paid any compensation for expropriated land.

Income

Income is generated at different levels of the value chain. The bauxite mine operators often represent elements of a vertically integrated aluminium producer , so that in this case world market prices are not paid for bauxite mine production, but instead internal transfer prices. For bauxite that is offered on the global market, a price per tonne from the mine ex work is determined in negotiations between the producer and the buyer. Prices depend on the recoverable metal content on the one hand and on price-reducing constituents on the other, such as reactive silicon oxide, titanium and iron oxide, and the moisture content of the raw ore. On average, the current price is approximately $US 30 – 45 /t ex works. For the customer, the transport costs, which depend on the means of transport and the transport distances, as well as the number of bulk transfers, are added to this.

The income from bauxite production also generates government revenues and employee incomes. Both are revenues that directly or indirectly benefit local people or the population of the country. Government revenues are made up of two components. On the one hand, there is the mining duty or royalty?, which is often calculated on a per-tonne or value-specific basis for bauxite, and on the other hand, the concession fees, i.e. the fees required to even be allowed to mine. Both revenues can often be derived from the respective national mining legislation and its subsidiary laws, or are stipulated in additional regulations. Another source of income for the state is corporate taxes (e.g. on profit, income, turnover, export proceeds, etc.), which result from corporate tax law, but also employee income tax. For the extractive sector in bauxite-rich Guinea alone, over 36 types of state taxes and fees are payable [13].

The contributions of aluminium‘s added value to a nation‘s economy can be substantial at all levels. The production value of the bauxite mine Weipa in Northern Australia is currently approx. $US 1.1 billion. Of this, the Australian state will receive approximately 10 % as taxes and royalties. The approximately 1,400 employees receive around 15 % of the sales proceeds as salaries or wages and thus strengthen purchasing power in the structurally weak region of northern Australia. Rio Tinto is the largest regional employer in northern Australia.

The share of mining in Guinea‘s gross domestic product was around 15 % in 2014. The share of bauxite mining in GDP, calculated using the production value, is probably around 9 %. Here, too, bauxite mining serves as a locomotive for local economic development.

In the case of Guinea‘s 2016 bauxite exports, the average price was $US 42 per tonne of raw bauxite. A total of 33 million tonnes of bauxite were exported in the same year, which corresponded to a total value of around $US 1.4 billion. The effective government revenue from this amounted to almost $US 280 million, which corresponds to an effective tax percentage of approximately 20 % [13].

4.3 Governance

Around two thirds of global mining production comes from countries with a medium to low governance rating (Worldwide Governance Indicators <0.5; [14], Fig. 5), i.e. with weak governance, or from countries with autocratic political systems. The Resource Governance Index [15], calculated as an average and weighted according to the country‘s bauxite production, has a value of 60 (on a scale of 0 to 100) for bauxite mining, which corresponds exactly to the boundary between satisfactory and poor resource governance. Only Australia, which leads in terms of production volume (around 30 % of production), has an above-average rating.

A large proportion of the aluminium industry is internationally networked, and the producers of aluminium are often fully vertically integrated. In order to guarantee a comparable standard, especially in the sustainability aspects of aluminium production, almost all well-known aluminium producers have joined forces in the Aluminium Stewardship Initiative (ASI). The ASI Performance Standard, according to which companies in the value chain (from mining to recycling) can be certified, corresponds to the international requirements for a certification initiative (ISEAL Code) and includes 59 requirements in the fields of environmental, social and corporate governance.

Since the programme began in 2017, there has been a strong increase in membership to currently more than 100 companies. More than 50 certifications have been issued to date. In terms of mining, 8 mines are currently certified, all 5 in Australia and 3 in Brazil. This corresponds to a total of around 30 % of global bauxite production.

Five of the ten largest bauxite producers are members of the International Council on Mining and Metals (ICMM), an international association of large raw material producers, and are therefore obliged to adhere to the 10 ICMM sustainability principles. Their production comprises around 40 % of global bauxite production.

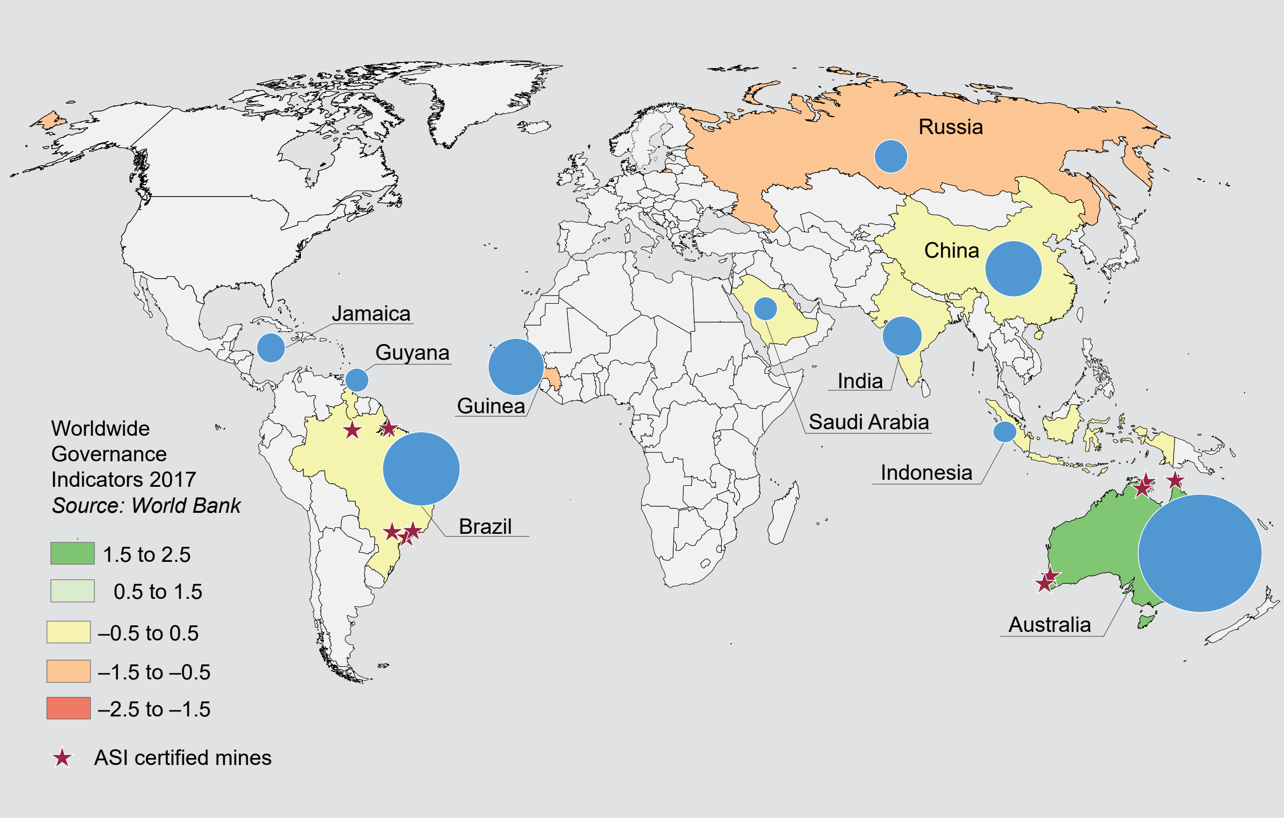

Fig. 5: *The 10 largest bauxite producing countries (2018) and their governance assessment compliant with the World Governance Indicators (WGI, [14]) and the locations of the mines certified by the Aluminium Stewardship Initiative (ASI).*

5 SUSTAINABILITY ASPECTS OF PROCESSING

Bauxite is processed to produce aluminium metal in two stages, which have vastly different environmental impacts. In the first stage, the alumina plant, the alumina is extracted from the bauxite (Fig. 6). Large volumes of caustic soda are used here, and the leaching residue must be disposed of.

In the second stage, the aluminium smelter, the alumina is melted in a metallurgical electrolysis process and reduced to aluminium, which is extremely energy-intensive (Fig. 7).

5.1 Environmental aspects of alumina production

Feedstocks and energy

Approximately 2.4 t bauxite, 85–100 kg caustic soda, 50 kg quicklime, 330 kg fuels (coal, oil and gas) and approximately 250 – 420 kWh of electrical energy are used to produce one tonne of alumina (aluminium oxide). In addition, the average water consumption in the Bayer process is 1.4 m³ per tonne of alumina [6, 16 and 17].

The average total specific energy consumption in the Bayer process is approximately 12 GJ per tonne of alumina. Approximately 90 % of this energy requirement is covered by fuels – primarily coal and natural gas – and around 10 % by electricity. In relation to the total German primary energy consumption, the energy consumption for global alumina production would be approximately 12 % of this value. The energy mix currently used worldwide results in average CO_2 emissions of approximately 570 kg per t CO_2 alumina. This corresponds to around 5 % of current pro capita CO_2 emissions in Germany.

Residues

In 2017 alone global alumina production amounted to around 127 Mt, which simultaneously resulted in the production of 155–175 Mt of solid process residues (red mud), which demanded environmentally compatible disposal in sludge ponds or landfills. The principal producers of alumina are China (69 Mt) and Australia (20 Mt), followed by Brazil (11 Mt) and India (6 Mt). Corresponding to their share in global production, the largest volumes of red mud are produced in these countries. Depending on the type of ore, between 1.8 and 3.2 t bauxite (dry) are used to produce 1 t of alumina, an average of around 2.3 t. Around 0.5 – 1.5 t of red mud (0.7 t on average) are produced per tonne of alumina production, or, based on the tonne of primary aluminium, around 1 – 3 tonnes of red mud. In the course of the production history of aluminium, around 4 billion tonnes of red mud have been disposed of globally.

The specific red mud volume depends primarily on the aluminium oxide content of the bauxite used. This is between 53 % for West African and Australian bauxite for export and around 38 % for poor ores from Australia and Central Asia. The chemical extraction yield in the alumina plant also plays a role and is typically between 94 – 96 %, depending on the adopted technology. Because of the relatively low content of the bauxite, a disproportionately large amount of red mud per tonne of alumina must be disposed of in China, Russia and Australia. In Europe less red mud accrues per tonne of alumina as a result of the relatively high aluminium content of the bauxite used. Red mud is a mixture of sand and a silt fraction (almost in equal parts). The majority consists of the insoluble iron and silicon impurities in bauxite and may contain small amounts of soda and carbonates, but also traces of heavy metals. In Germany, red mud is classified in Landfill Class 0 and is therefore less hazardous than household waste (Class 1). When assessing the red mud landfill hazard, the risk of physical collapse of the landfill structure can be distinguished from the risk of chemical pollution of groundwater and soil by heavy metals and alkalis. Red mud landfills can assume considerable dimensions. Heights greater than 20 m and storage capacities over 10 Mm³ are not uncommon. Red mud is highly saturated with water. When planning the landfill, it must be assumed that the red mud itself has little or no inherent strength. Red mud deposits must therefore be contained and the landfill subsurface sealed if water is not removed from the sludge beforehand, in order to ensure physical stability and avoid infiltration into the subsurface. In addition, the water with the dissolved constituents should be recirculated in the leaching process.

Due to the shortage of emplacement areas and increasing concerns about the final disposal of red mud, what is known as the dry stacking method was introduced in the mid-1980s, enabling higher landfills to be constructed. Using this method, the residues are dewatered by high-performance thickeners (to a solids content of approx. 48 – 55 %) before going to landfill and then emplaced in a way that enables further drying and solidification.

Fig. 6: *Gladstone alumina plant in Australia, photo: courtesy of Rio Tinto.*

Fig. 7: *Straumsvig aluminium smelter in Iceland, photo: courtesy of Rio Tinto.*

Another method currently widely used is filtration, e.g. using a vacuum filter or in a filter press, whereby a filter cake (typically < 30 % residual moisture) is produced. The cake is washed with water or steam to reduce alkalinity before being sent to landfill. Because of the lower alkalinity, cheaper transport and easier handling, drying the residue by filtering is preferable to the dry-stacking method, pipe discharging the red mud in ponds or dumping into the ocean.

In Germany, the sludge is now emplaced in sealed landfills. The dispersed hydroxides and silicates settle out of the mud flow and an unconfined water level forms on the landfill surface. From there the water, which still contains caustic soda, among other constituents, is recycled.

Once the landfill has reached capacity, it is covered with a layer of coarse-grained tailings – if available – and a water-retaining clay or loam layer. The applied topsoil is then recultivated. There have also been successful attempts to plant the red mud directly after applying soil improvement measures.

A previously common method was to dispose of the red mud into rivers, lakes and estuaries with the aid of pipelines, or dumping directly into the ocean. This technique is now rarely used by the major alumina producers. In Greece and France, however, this disposal method is still employed.

The short-term hazard presented by red mud is primarily due to the caustic soda content. Long-term harm results from the toxic heavy metal content, which primarily depends on the origin and mineralogical composition of the bauxite. Heavy metal oxides and hydroxides are, however, only very poorly soluble in a alkaline medium. Red mud in landfill contains around 1 % soluble heavy metal hydroxides.

Possible reuse of red mud for other purposes in order to allow the volume of residues from alumina production to be reduced has been researched for some time. However, larger quantities of red mud are currently not being usefully exploited elsewhere. Red mud that has been reacted with sulphuric acid can be used to a certain extent as a flocculant in sewage treatment plants and as an alkaline base liner for landfills that generate acidic water. However, the applications mentioned constitute a maximum of 1 % – 5 % of the total red mud generated in alumina production.

During leaching, the elements scandium, gallium, phosphorus and titanium, as well as the rare earth elements, are also concentrated in the red mud. Occasionally, scandium and gallium are obtained as by-products of alumina production from the Bayer process aluminate-containing solution by electrolysis, fractional precipitation or using chelating reagents.

5.2 Environmental aspects of aluminium smelting

Feedstocks and energy

An average of around 2 t of alumina, 370 kg of coke and 116 kg of tar pitch for anode production, 15 – 30 kg of synthetic cryolite and around 13 – 15 MWh electrical energy is required to produce 1 t of primary aluminium. This corresponds roughly to the annual electricity consumption of three to four 4-person households in Germany. Electrical energy consumption for global aluminium production alone would account for approximately 37.5 % of Germany's total final energy consumption, which was around 2,500 TWh in 2018.

Primary aluminium is produced from alumina in aluminium smelters, which are mainly located in China and countries with cheap energy sources (Table 1).

***Tabele 1:** The most important primary aluminium producing countries 2017 [4].*

Rank	Country	Mt	Percentage
1	China	32.3	55.2%
2	Russia	3.7	6.4%
3	Canada	3.2	5.5%
4	UAE	2.7	4.6%
5	India	2.0	3.5%
6	Australia	1.5	2.5%
7	Norway	1.3	2.1%
8	Bahrain	1.0	1.7%
9	Saudi-Arabia	0.9	1.6%
10	Iceland	0.9	1.5%
	others Federal	9.1	15.5%
	Total	**58.5**	**100%**

Fluoride emissions

Probably the greatest emission problem of the aluminium smelters is that of fluoride emissions, which come from the molten cryolite and other aluminium fluorides required for electrolysis, and which can be released into the environment via the smelter's central stack. Depending on the adopted anode technology (Söderberg, Prebake, Prebake + Söderberg), the emissions in 2017 were between 0.6 – 1.7 kg fluoride/t aluminium. Emissions can be reduced through the use of flue gas control systems, improved electrolytic cell charging methods and improved anode technology. However, the fluoride emissions from modern smelters are not classified as a high health risk for humans.

Greenhouse gases

Small quantities of the highly potent greenhouse gas PFC (perfluorinated hydrocarbons) can be generated by process anomalies known as anode effects. The magnitude of the anode effects depends on the adopted process and the state of metallurgical technology. This anode effect should be kept as low as possible by means of good production systems. The average greenhouse gas emissions of PFCs are given in CO_2 equivalent (CO_2e). As a greenhouse gas, a PFC molecule is approx. 6,500 times more potent than a CO_2 molecule. The share of PFCs in the total greenhouse gas emissions of the aluminium smelter is around 5 %.

Oxidation of the anode material during the process creates CO_2 as an additional greenhouse gas. Between 0.42 and 0.45 t of anode material are used per tonne of primary aluminium, which theoretically corresponds to production of around 1.6 t of CO_2 per tonne of aluminium. Globally, primary aluminium production caused greenhouse gas emissions (through the use of heat and electrical energy as well as carbon as a reducing agent) of around 1.08 Bt CO_2e, which corresponds to a specific emission of around 18 t CO_2e/t aluminium [5]. For comparison: the annual CO_2 emission per capita in Germany is 7.9 t. In particular, the greenhouse gas potential depends on the smelter's energy supply. In Norway and Iceland, for example, electricity from hydropower, which has a low greenhouse gas potential, is mainly used.

Indirect effects on the environment and the population from aluminium production are possible as a result of using reservoirs for power generation, because the necessary electrical energy is provided by hydropower in numerous smelter locations. Examples of this can be found in Central Asia, West Africa, Northern Europe and South America. In China and Mozambique, some aluminium smelters have been accused of sloppy compliance with atmospheric emission standards [12].

5.3 Social and socio-economic relevance

Compared to other metal resources, primary aluminium production has the largest share of added value in processing and smelting, while for non-ferrous and precious metals it lies in mining. In 2018, the total value of primary aluminium was around $US 118 billion, that of alumina around $US 57 billion and that of bauxite around $US 11 billion only. Because bauxite is a bulk raw material, the cost share for capital investments and energy in processing and aluminium production is relatively high. However, the proportional value of bauxite production in the added value chain continues to increase. In 1999 it was only around 6.4 % of the production value of aluminium, in 2017 it was already 9 %. The costs of alumina production are also increasing. In 1999 they amounted to 27 % and in 2017 to 40 % of the total value added. Around 50 % of the added value in 2017 was accounted for by the transport and production of the raw aluminium in smelters. Taking into account that the nominal aluminium price has remained almost unchanged since the 1960s, this shift in the value-added shares is mainly due to the more energy-efficient smelting processes and the economies of scale in the transport of bulk goods.

Because processing is extremely energy-intensive and energy costs constitute 20 – 40 % of the total costs, alumina refineries and smelters are generally located close to cheap energy sources (Iceland, Norway, Bahrain, Russia, Australia), or they are located close to the customers in the heavily industrialised countries (EU, North America, China). Due to the balanced economic development in these industrialised countries and regions, the importance of the aluminium sector for macroeconomic development should be regarded as minor.

5.4 Governance

The governance aspects of bauxite processing to aluminium metal are intricately linked to the mining side of the production chain, as the large aluminium producers usually directly or indirectly own the upstream chain or are capable of exerting a strong influence on the upstream sector through supply contracts. Questions around mining-related conflicts and the comparatively high energy demand for aluminium production are also in the focus of a critical public, governments and end users (original equipment manufacturers, OEMs) worldwide. It is therefore not surprising that aluminium producers, especially those who are committed to the Aluminium Stewardship Initiative (ASI), have a pioneering role in the raw materials sector in terms of transparency and production standards, at least in Europe, North and South America, Russia, China and Australia. Of the approximately 85 large alumina plants and 150 aluminium smelters around the world, 57 processing companies are currently certified according to the ASI standards.

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EDITORIAL

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© Bundesanstalt für Geowissenschaften und Rohstoffe
(Federal Institute for Geosciences and Natural
Resources, BGR)
B 1.2 Geology of Mineral Resources Department
Mining and Sustainability Unit
Stilleweg 2
30655 Hannover

E-Mail: mineralische-rohstoffe@bgr.de
www.bgr.bund.de

Authors:
Jürgen Vasters und Gudrun Franken

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Jolante Duba

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